MODELING AND ANALYSIS OF MASONRY ELECTRO-THERMAL HEATING AND STORAGE FOR OPTIMAL INTEGRATION WITH REMOTE STAND-ALONE WIND-DIESEL SYSTEMS

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Abstract

Due to their remote locations and small populations, many remote villages in Alaska generate electricity with microgrids that employ diesel-electric generators for their primary source of power, and supplement this production with wind turbines. In such communities, it is economically advantageous to minimize fuel consumption by shifting as much of the village's energy demands to the wind system as is feasible. When wind turbines produce in excess of the demand, it is possible to use the excess electricity to power resistance heaters to heat water in tanks or masonry. The heat is then stored so that it can be used immediately or in the future to meet the village's heating demand. This is called electrothermal heating (ETH). The goal of this research work is to use MATLAB/Simulink® to model heating scenarios employing masonry electrothermal heaters to investigate how excess electricity from wind can be used for immediate heating needs and storage. The results demonstrate reduced heating oil consumption using electrothermal heating and increased storage potential in conjunction with oil stoves.

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ABBREVIATIONS

AHFC-Alaska Housing Finance Corporation

CHP– Combined Heat and Power

CRF-Capital Recovery Factor

COE-Cost of Energy

DEG–Diesel Electric Generator

ETH–Electro-Thermal Heating

NPV-Net Present Value

NREL-National Renewable Energy Labs

TES-Thermal Energy Storage

NOTATION

C – Heat capacity (unitless)

c - Scale Parameter

c_p –Specific Heat (BTU/(lb-°F))

H – Efficiency of Heat Exchanger (unitless)

k – Thermal Conductivity (BTU/(h-ft-°F))

κ- shape parameter

m – Mass (kg)

$\dot{m}$– Mass Flow Rate (lb/s)

η– Efficiency (Unitless)

Q – Energy (BTU)

$\dot{q}$ – Rate of Energy Flow (BTU/h)

$\dot{q}_{demand}$– Rate of Energy (BTU/h)

$\dot{q}_{lost}$ – Rate of Energy Lost (BTU/h)

R_{eq} – Thermal resistance (ft^2-°F/BTU)

T – Temperature (°F)

T_h– Temperature of Heater (°F)

T_r– Temperature of Room (°F)

T_{in} – Temperature In (°F)

T_{out} – Temperature Out (°F)

V – Voltage (V)

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Chapter 1: Introduction

1.1 Introduction

Rural, coastal Alaskan villages which experience relatively high average wind speeds are ideal candidates for wind power. Diesel electric generators (DEGs) are the primary source of electricity in these communities. However, diesel fuel is expensive due to the fact that it must be transported by barge. Wind turbines also produce electricity, but the quantity of electricity produced is not always predictable because wind speeds are highly variable and dependent on a number of factors such as the weather conditions and season. Electricity generated in excess of the load from wind can be re-directed from the primary electric load to a dump load. A dump load is a secondary load used to sink excess energy, and in the case of wind turbine generation, provide stability to the system. In this case, the dump load may simply be a resistive heater that heats water or masonry. This is called electro-thermal heating (ETH). Water or masonry will store the heat energy until it can be used (either by pumping the water to meet the hot water demand, or by using a blower to release the heat from the water or masonry into the space to be heated).

This project aims to develop and use MATLAB/Simulink® models to explore how a standalone grid can utilize excess wind energy with ETH to heat homes and community buildings. Ideally, the model will show ways in which a higher percentage of the village's total heating needs can be met with renewable wind power as opposed to expensive, non-renewable diesel.

The goals of this project are to:

1. Create Simulink® models of electrothemal masonry heaters, and adapt them to existing facilities.

2. Adjust the models and simulate heating and storage scenarios to:

    - Reduce the use of heating oil

- Optimize heating cost

A viable ETH system must be compatible with the existing heating and electrical power system and have an economical payback time.

1.2 Background

Rural Alaskan communities have high heating costs due to the high cost of heating oil used in oil stoves for residences and some community buildings. Waste heat from diesel cooling loops is used as a district heating resource in some of these communities, but only for large buildings like schools and community centers. The percentage of fuel use by sector in rural Alaskan communities below is dominated by space heating as illustrated in the pie chart in Figure 1.

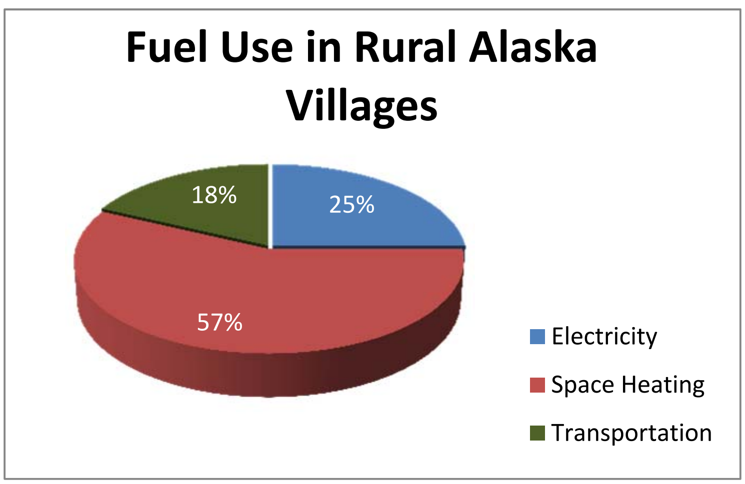

Figure 1: Fuel Use by Sector in Rural Alaskan Communities [1]

The communities that will be examined in this project are Unalakleet and Kongiganak, Alaska, shown on the map in Figure 2. Each community is located on the west coast of Alaska, where heating and diesel oil are delivered by barge. Shipping oil is expensive and requires additional energy from transportation. Each town is on a wind-diesel microgrid that generates electricity primarily with diesel-electric generators, and secondarily with wind. These communities will be modeled because they are representative of different microgrids in coastal, rural Alaska. Kongiganak presently has 100 Steffes units installed, whereas Unalakleet has none [2]. Steffes units are masonry electrothermal heaters and storage devices on which this thesis will focus.

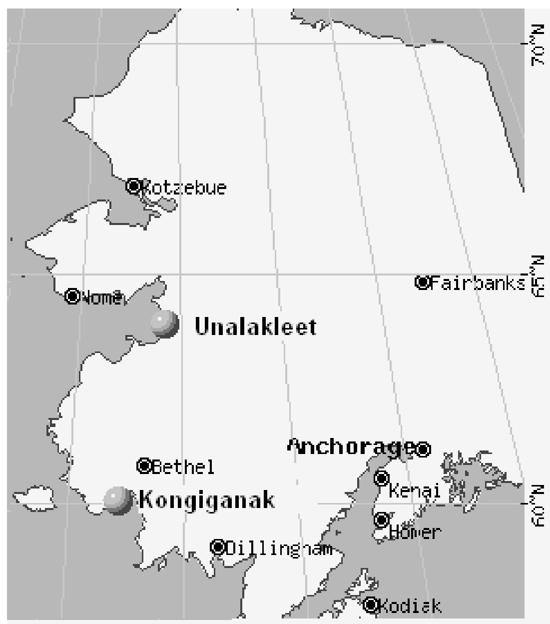

Figure 2: Map of the Communities in Alaska [2, 3]

1.2.1 Kongiganak

Kongiganak is located about 451 miles west of Anchorage, on the west shore of Kuskokwim Bay, as shown in Figure 2. The village is located at 59.95° north latitude and 162.89° west longitude. According to the 2010 census, the population of Kongiganak is 439. There are 90 houses (some unoccupied), and several public buildings, including a school and community center [4]. The average wind speed is 7.9 m/s, or 17.8 mph, making it a class 6 wind site. Its temperatures throughout the year range from 6 °F to 57 °F, with an average temperature of 8.3 °F [5].

Kongiganak's power needs are met with four diesel powered generators and 5 Windmatic 17S wind turbines, which convert kinetic wind power (to be addressed in section 2.3.4) to electrical power at 25% efficiency, which was determined through an independent study by the National Renewable Energy Lab (NREL) [2]. In 2010, it is estimated that the average homeowner consumed 766 gallons of heating fuel at a cost of over $7.10 per gallon [4]. Average diesel usage is 187 gallons per person at $5.42/gallon [4]. The cost of energy, including heat, transportation, and electricity is $3,222 per person, and the average per capita income is $8,346. Many community residents practice subsistence fishing and hunting [4]. The community has already installed 100 masonry heaters to use excess wind energy for heating individual homes and community buildings [2].

1.2.2 Unalakleet

Unalakleet is located on Norton Sound at the mouth of the Unalakleet River, 148 miles southeast of Nome and 395 miles northwest of Anchorage as shown in Figure 2. Wind speed data for Unalakleet is collected at a 40 foot elevation. Alaska Energy Authority gives the average windspeed in Unalakleet as 7.7 m/s, or 17.2 mph [6]. According to the 2010 census, there were 268 housing units in the community, 225 of which are occupied with 747 people [7].

Unalakleet's power needs are met with four diesel powered generators and 6 Northwind 100 wind turbines, which convert wind into electricity at 30% efficiency, when taking into account the inefficiencies of starting the generators and varying windspeeds [8]. In 2010, diesel fuel cost were $4.48/gallon, and heating fuel costs were $4.98/gallon [6]. The community used 304,977 gallons per year, or 1,355 gallons of fuel per house, for an annual cost of $6,747.90 per household [6].

1.3 ETH in Wind-Diesel Systems

In isolated high-penetration wind-diesel microgrid systems, wind power becomes the primary source of electricity. When wind power fails to meet the electric demand, diesel generators power the grid. When wind energy is in excess of demand, the excess is discharged and wasted as a dump load. If excess electricity from wind can be harnessed to meet some of the heating load, the village can reduce its use of heating fuel, saving money and reducing the environmental impact of transporting and burning fossil fuels.

1.3.1 Heating

Heating is a major cost of living in Alaska. Housing in Alaska is designed for cold climates. Walls and ceilings are designed to have high thermal resistance. Heaters (usually oil heaters) provide domestic heat. If it is possible to reduce the amount of heating oil used to heat domestic residences, individuals could spend less to heat their houses.

1.3.2 Combined Heat and Power

Combined heat and power (CHP) is the principle of generating heat from methods ordinarily used only to generate electricity, such as ETH from fluctuating power created by the wind turbines, and jacket water around the diesel-electric generators (DEGs). The concept of combined heat and power is illustrated in Figure 3. This flowchart illustrates the conversion of wind to power, and eventually electricity and electric heating, as well as diesel fuel to heat to electricity via a heat pump.

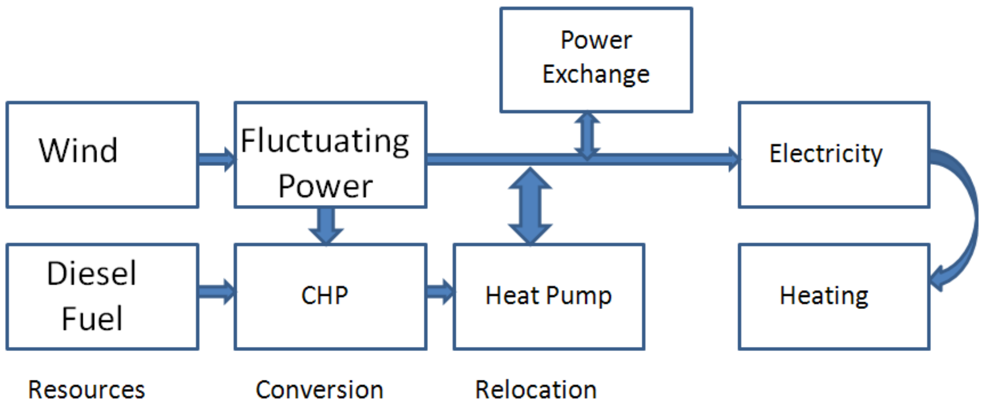

Figure 3: Combined Heat and Power Block Diagram

When DEGs are turned on, the combustion of the diesel fuel creates heat, which can be collected with coolant jacket water and heat exchangers. Water flows through the DEGs in a cooling loop at a low temperature, is heated by the DEGs, and used to meet the heating demand.

1.3.3 Displacing Heating Fuel

Calculating how much energy the villages require to maintain comfortable indoor building environments determines how much heating oil is needed. Once the amount of oil and its cost is calculated, it can be compared to the cost of installing, maintaining and using a substitute method of storing and distributing heat. The amount of energy required to maintain a comfortable temperature is the total energy lost and demanded over a period of time as given by Equation 1.1 [9]

$$Q = \eta \int (\dot{q}_{lost} + \dot{q}_{demanded})dt \tag{1.1}$$

where Q is the total energy used, η is efficiency of the system, and $\dot{q}_{\mathrm{demanded}}$ and $\dot{q}_{\mathrm{lost}}$ are the rates of power demanded and energy lost, respectively.

1.4 Methods of Heating and Thermal Energy Storage (TES)

Capturing and storing heat is a unique challenge for each thermal-electric system. Figure 4 shows the process for hot thermal storage: the storage material is ‘charged’ when it is heated with resistance heaters (to be discussed in Section 2.1). This energy is either used immediately or stored over a period of time during which heat is lost to the surrounding environment. Heat energy is extracted from the system for use when needed through convection of a working fluid, usually air, water or glycol.

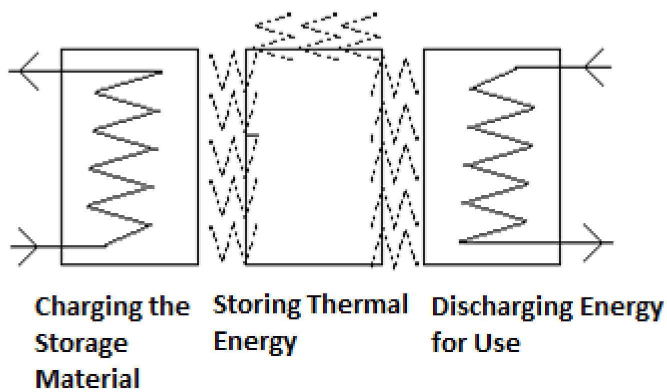

Figure 4: Heating and Thermal Energy Storage Process

A well-designed system charges easily, loses minimal energy to the environment, and distributes energy easily on demand. The equations which describe the charging and discharging of the storage materials depend on the method of charging and the type of storage material. The amount of heat stored can be expressed as Equation 1.2 [9]

$$Q = mc_p\Delta T \tag{1.2}$$

where m is the mass (lb), c_p is the specific heat (BTU/lb-°F), and ΔT (°F) is the temperature rise (T_{final} - $T_{initial}$) of the storage material from its initial 'uncharged' state to its final 'charged' state [9].

1.4.1 ETH in Water Tanks

Water is a great storage medium because it is readily available, and has a relatively high specific heat and density. It can be used to store energy and distributed, or can transfer energy to a secondary heat transfer medium. Storage tanks of water can be heated easily with resistance heaters which convert the delivered electric energy into thermal energy with nearly 100% efficiency [10]. A simplified thermodynamic model of a boiler is shown in Figure 5.

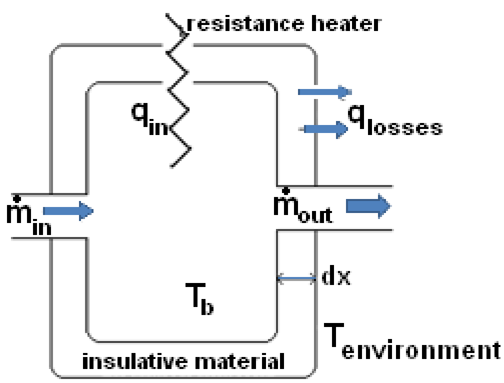

Figure 5: Simplified Thermodynamic Model of a Boiler

The heat balance of a hot water heater is given by Equation 1.3 [9]

$$Q_{stored} = \int (\dot{q}_{in} - \dot{q}_{loss} - \dot{q}_{demand} + \dot{q}_{replacedwater})dt \qquad (1.3)$$

where $\dot{q}_{\text{in}}$ is the energy that enters the tank through the voltage across the resistive heater, $\dot{q}_{\text{loss}}$ is the heat loss through the wall of the heater, and $\dot{q}_{\text{demand}}$ and $\dot{q}_{\text{replaced water}}$ are the energy that flow out and return to the heater due to demand and return hot water, respectively.

1.4.2 ETH with Masonry Bricks

Bricks are a good storage medium because they are inexpensive, relatively easy to charge and discharge, dense, and have a high heat capacity. They are charged by resistive heaters. A 2010 project proposed Kongiganak install Steffes 2106 room heating units (Figure 6) into individual homes [4]. These heaters use resistive heating elements to heat the bricks, and a thermostatically-controlled fan to blow air over the hot bricks to release the heat to the room.

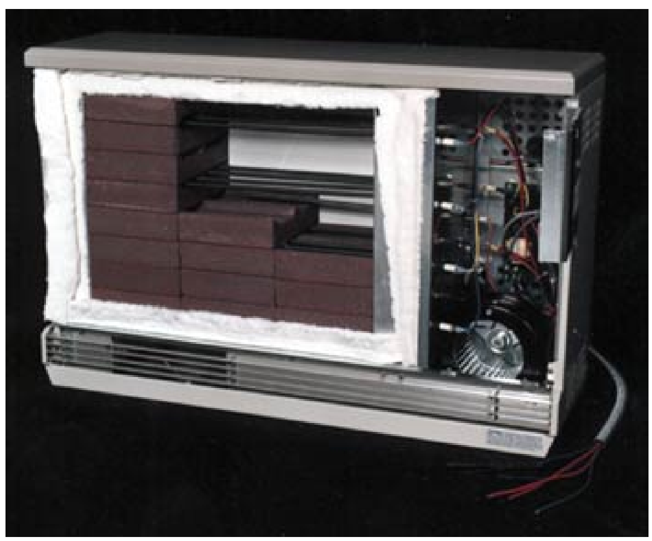

Figure 6: Steffes Room Heating Unit [11]

Figure 7 shows a cut-away view drawing, including the configuration of resistive heaters, bricks, blowers, and insulation. Thin bricks are packed close together with resistive heaters between rows of larger bricks. The blowers force air across the brick mass to move the heat from the bricks to the ambient air.

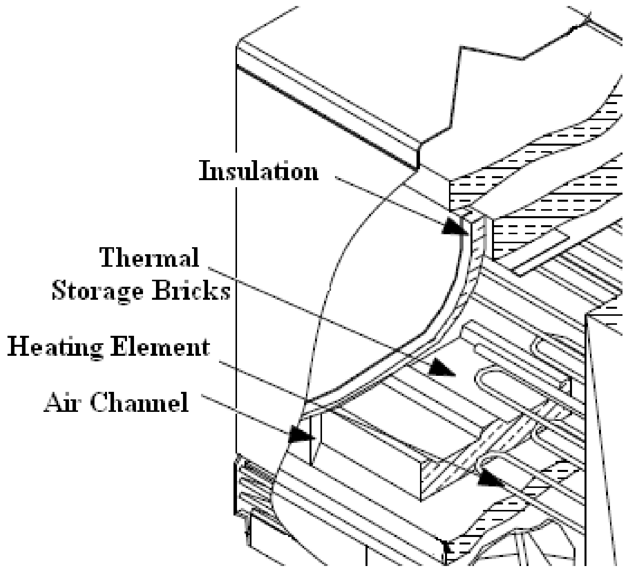

Figure 7: Cutaway View of Steffes Heating Unit [12]

Steffes, the manufacturer, recommends heating units for short-term energy storage. These units were designed for certain geographic markets using "off-peak power", power generated during hours when electric demand is low. These masonry heaters 'charge' during nighttime when electricity is cheaper, and distribute heat during the day. In Alaska, the benefit is that electricity can be harnessed from wind power or solar power, which is sporadically available, and released as it is needed.

1.5 ETH Model with MATLAB/Simulink®

In this thesis the masonry ETH system is modeled in MATLAB/Simulink® for different heating and storage scenarios. Simulink® is used to model the ETH system primarily because:

- It supports linear and nonlinear systems, modeled in continuous time and/or discrete time.

- It can model, analyze, and simulate dynamic systems.

- The ETH models can be integrated into a dynamic hybrid wind-diesel model that is also being developed in MATLAB/Simulink®.

Six scenarios for the masonry ETH will be modeled and evaluated for accuracy in an increasingly complex order as follows:

1. Steffes heater charging and discharging with no environmental losses.
2. Steffes charging and discharging with losses.
3. Steffes charging and discharging in a perfectly insulated house.
4. Steffes charging and discharging in a house that loses heat to the environment.
5. Steffes charging and discharging in a house that loses heat to the environment, with thermostatic controls.
6. Year-long analysis: Temperature charge controller keeps Steffes charged and thermostat keeps house at comfortable temperature.

In order to develop the model, the mechanics of the Steffes heater must be understood, so that the appropriate equations may be applied. Chapter 2 discusses the theory behind all models. The models are then developed, simulations are run, and results are evaluated for reasonability in Chapter 3. Chapter 4 shows the thermal-electric and economic simulation results and analysis of various ETH scenarios using the models with actual wind speed and ambient temperature data from two rural Alaskan communities. Finally, conclusions and future work are presented in Chapter 5.

Chapter 2: Electrothermal and Oil Heating Model Theory

2.1 Components of the System

The major components of this system include the electrothemal devices (masonry and hot water heaters), oil heaters, and buildings with and without a thermal envelope. Hot water heaters are modeled as a means of understanding electrothermal heating and storage. The diesel electric and wind turbine generators are not independently modeled, but their power outputs are used as inputs to the electrothermal device models. The components, once developed and validated, are used in various test systems to investigate the potential economic benefits of electrothermal heating from wind generation to displace heating oil. Each test system must be modeled as the sum of its components. It is easy to visualize each component in terms of energy in, and energy out, knowing that each complete system must account for all energy. The rest of this chapter discusses the system components based on theoretical, material, and manufacturer specifications, followed by model development and validation using known operating conditions applicable to a rural Alaskan community in Chapter 3.

2.1.1 ETH Masonry Heaters

The Steffes heater will be modeled as the subject of this research. The Steffes can be installed in any building with 120 VAC or 240 VAC service so minimal infrastructure changes are needed; only new electric circuits to provide 240 VAC at 7.2 kW to the heaters as discussed in Chapter 4. As discussed earlier, the Steffes uses excess electricity from wind to heat masonry bricks with resistive heating elements. Converting energy from electric voltage (V) to a thermal output (BTU/h) with a resistance heater can be modeled as a lossless system, as specified by the U.S. Department of Energy [10]. When the amount of energy stored in a fully charged system, and the rate of heat flow in and out of a system are known, models of the plant can be developed and simulations performed to determine the time it takes to fully charge or discharge a system. This equation is most basically given by Equation 2.1 [9]

$$Q_{stored} = \int (\dot{q}_{in} + \dot{q}_{demand} - \dot{q}_{loss})dt \tag{2.1}$$

where $\dot{q}_{in}$ is given by Equation 2.2 [9]

$$\dot{q}_{in} = \left(\frac{V^2}{R}\right) \tag{2.2}$$

where V is voltage (V) and R is the resistance (Ω) of the heating elements. $\dot{q}_{\mathrm{loss}}$ is given by Equation 2.3 [9]

$$\dot{q}_{loss} = kA\frac{\Delta T}{x} \tag{2.3}$$

where x is the thickness of the insulation (ft), k is the thermal conductivity of each material (BTU/(hr-ft-°F)), A is the surface area of the heater that loses heat to the outside (ft^2), and ΔT (°F) is the temperature difference ($T_{heater} - T_{house}$) between the storage material and the house. Because the heating elements between the bricks are close enough together that the temperature variation in the bricks is negligible, calculations reveal that they can be modeled as steady-state. $\dot{q}_{demand}$ has been given by Steffes as 20,000 BTU/h when the thermostat turns the blower on, and is 0 otherwise.

From Equation 1.2, one can also see that a good storage material has a high specific heat value and has a high mass, due to high density or feasibility of storing a large quantity of heat in the material. For this reason, brick is used, which has a specific heat of about 0.32 BTU/(lb-°F) [10]. Coupled with its high mass (about 528 pounds of brick are placed in the Steffes), masonry brick is excellent for storing large quantities of heat in a small space. The Steffes heater is designed to replace or supplement the heat provided by a Toyo oil stove. A Toyo stove, discussed in the following section, is the most common way to heat a house in an Alaska village.

2.1.2 Oil Heating Stoves

Oil stoves (Toyo heaters) are relatively efficient (~87%) and easy to operate [13]. Oil stoves work by pumping #2 heating oil to the flame when the thermostat determines that it is necessary to reach the set point. The Toyo Miser, with flow diagram and front of unit shown in Figure 8 and Figure 9, pumps 20,000 BTU/h into the room when it burns #2 heating oil rated at 138,5000 Btu/gallon, burning about 0.19 gallons of fuel per hour [13].

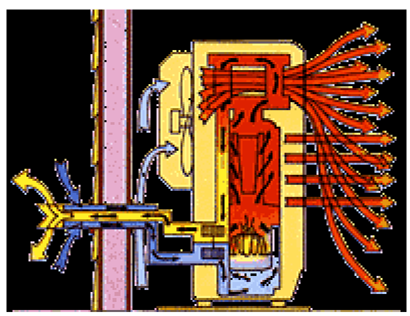

Figure 8: Toyo Oil Heat Stove Operation [13]

Figure 9: Toyo Oil Miser [13]

A Toyo stove is simply modeled as a device which converts heating oil at 135,000 Btu/gal to heat at 87% efficiency [13]. This is described by the relationship in Equation 2.4

$$\dot{q}_{heater} = (138{,}500\ \mathrm{BTU/gal})(0.19\ \mathrm{gal/h})0.87 = 22{,}894\ \mathrm{BTU/h} \qquad (2.4)$$

where $\dot{q}_{heater}$ is either delivering 0 BTU/h of heat or 22,894 BTU/h as the thermostat is off or demands heat, respectively.

2.1.3 Building Models

In general, thermal energy enters a house through the heater, both from the thermostat switching on the heat by demand, as well as from losses from the heater and leaves the house through the insulation. The overall building heating plan can be described by Equation 2.5 [9]

$$Q_{stored} = \int (\dot{q}_{demand} + \dot{q}_{heaterloss} - \dot{q}_{loss})dt \qquad (2.5)$$

where $\dot{q}_{demand}$ is the heat that is distributed when the thermostat turns on the blowers (Steffes claims that this is 20,000 BTU/h at average output), $\dot{q}_{heaterloss}$ is the loss of energy from the heater to the house given by Equation 2.6, and $\dot{q}_{loss}$ is the heat loss from the house to its environment as in Equation 2.7 [9]

$$\dot{q}_{heaterloss} = \frac{T_h - T_r}{R_{eq(heater)}} \tag{2.6}$$

$$\dot{q}_{loss} = \frac{T_r - T_{out}}{R_{eq(room)}} \tag{2.7}$$

where T_h, T_r, and T_{out} are the temperatures of the heater, room, and outside, respectively, and $R_{eq(heater)}$ and $R_{eq(room)}$ are the equivalent thermal resistances of the insulation of the heater and the house. $\dot{q}_{heaterloss}$ must be determined since it is impossible for the heater to have perfect insulation, and therefore, store heat indefinitely.

For a building, R_{eq} is determined by the thermal resistances of the walls, floor, roof, doors and windows of a building. When a wall is composed of several layers, the resistance of the wall is calculated in series according to Equation 2.8

$$R_{eq} = \frac{x}{kA} \tag{2.8}$$

where x is the thickness of the insulation (ft), k is the thermal conductivity of each material (BTU/(h-ft-°F)), and A is the surface area of the heater that loses heat to the outside (ft^2).

The total resistance of the layers of the wall (gypsum board, blue foam, and siding) is given by Equation 2.9

$$R_{eq} = \Sigma R_n \tag{2.9}$$

In determining the total thermal resistance of a building or a room, the four walls, roof, and floor are calculated in parallel as given in Equation 2.10

$$\frac{1}{R_{Total}} = \frac{1}{R_{roof}} + \frac{1}{R_{wall\,1}} + \frac{1}{R_{wall\,2}} + \frac{1}{R_{wall\,3}} + \frac{1}{R_{wall\,4}} + \frac{1}{R_{floor}} \tag{2.10}$$

The outside temperature is given by meteorological data. The heater temperature is determined by how much energy is stored in the heater ($Q = mc_p\Delta T$) and the room temperature is a function of how much energy is stored in the air in the room using Equation 1.2 which is determined by an energy balance using Equation 1.3. The temperature of the room is then taken from the integral of Equation 2.11

$$\frac{dT_{room}}{dt} = \frac{1}{m_{air}C}(\dot{q}_{heater} - \dot{q}_{losses}) \tag{2.11}$$

where m_{air} is the mass of air inside the house (lb), C is the heat capacity of the air (BTU/(lb-°F)), $\dot{q}_{heater}$ is the rate of heat transfer from the heater to the room (BTU/h), and $\dot{q}_{losses}$ is the rate of heat transfer from the room to the outside (BTU/h). This equation is of course, a simplification for the sake of creating a simple model that treats the air in the house as one isothermal mass of air. The ramifications of this simplification will be expounded upon in section 5.4.

2.1.4 Hot Water Heaters

Water is a useful heat storage medium since it both stores and transports heat energy. It can simply be pumped into the tank for charging and pumped out for use. Because the energy that goes into a hot water tank varies with time, the hot water tank does not operate under steady-state conditions, and a differential equation must be derived in terms of the energy in (from the resistive elements) and energy out (through losses and charging the demanded water). To simplify calculations, the model assumes that the water temperature is uniform throughout the tank. The actual water tank will experience slightly higher temperatures (ΔT of 5-6 °F for 23 inch diameter tanks and insulation values of R-40, reaching internal temperatures of 140 °F) at the heating element as compared to the tank outlet [9].

The heat balance of a hot water heater is Equations 2.12 [9]

$$Q_{stored} = \int (\dot{q}_{in} - \dot{q}_{loss} - \dot{q}_{demand})dt \tag{2.12}$$

where $\dot{q}_{\text{in}}$ is the energy that enters the tank through the voltage across the resistive heater, as given by Equation 2.2, and $\dot{q}_{loss}$ as given by Equation 2.6 [9]. $\dot{q}_{demand}$ is the energy that is lost when the heated water leaves the hot water tank, as given by Equation 2.13 [9]

$$\dot{q}_{demand} = \dot{m}(t)[c_p(T_{in}(t) - T_{out})] \tag{2.13}$$

where $\dot{m}(t)$ is the mass flow rate, and c_p is specific heat of water, and T_{in} is the water coming into the tank at 40 °F and T_{out} is the temperature of the outflow of the tank, at the demanded temperature. This equation indicates the amount of energy inflowing water receives from the resistance heater to reach demanded temperature.

2.2 Buildings, Facilities and Heating Sources

For simplicity, three sizes of buildings are modeled for each community: small houses, big houses, and municipal facilities such as community centers. These buildings are all modeled with a thermal resistance of R-20 based on data from the Alaska Housing Finance Corporation (AHFC), which dictates that new walls in the Bethel and Nome climate zones (where Kongiganak and Unalakleet are located, respectively) be R-30, and by observations by the Cold Climate Housing Research Center (CCHRC), that walls in some villages can range from R-15 to R-20 [15, 16, 17]. R-values are a construction term for thermal resistance, given in units of ft^2-°F-h/Btu, and used in Equations 2.6 and 2.7. Building dimensions, volume, surface areas, and the number of Steffes units used in each building model are given in Table 1.

For simplicity, convection from the wind is not taken into account, but rather assumed to be infinite, so that the inside wall is modeled as being the same temperature as the thermal mass of air, and the outside wall of the structure as being the same temperature as the air. This makes the building model appear to lose more heat than it actually does, which slightly overestimates the heating demand.

Table 1: Building Parameters for Steffes Model

Building Parameters	Small House	Big House	Community Center
Size (l×w×h) ft	20×30×10	30×40×20	20×45×30
Volume of Air (ft^3)	6,000	24,000	108,000
Surface Area (ft^2)	2200	5200	9800
Quantity Steffes Units	1 Steffes	1 Steffes	2 Steffes

The total electro-thermal demand of all buildings in the community is the sum of the electric, heating, and hot water demands, necessary to maximize the efficiency of the system.

2.2.1 Community Buildings and Heating Sources

2.2.1.2 Kongiganak

Kongiganak has 76 occupied residential houses, three slightly larger buildings, (laundromat, clinic, and small local store), and six community buildings (water treatment plant, school, power company, community hall, fire hall and public safety building), as well as a bulk fuel storage facility [3]. The 76 houses and three slightly larger buildings were historically heated with Toyo oil stoves, and Steffes units were installed in Spring 2012. The six community buildings use district heating piped through a heat exchanger on the diesel electric power plants cooling loop. Bulk diesel fuel costs were $5.42/gallon and heating oil costs were $7.10/gallon in Kongiganak (2010) [3].

2.2.1.2 Unalakleet

Unalakleet has 225 occupied residential houses, and ten community buildings (school, water filtration plant, sewer plant, city office building, a post office, a clinic, native village office, fish plant, community hall, and an old downtown office) [6]. The 225 houses are heated with Toyo oil stoves. Bulk diesel fuel costs $4.38/gallon and heating oil costs $5.35/gallon in Unalakleet (2010) [19]. The six community buildings use district heating piped through a heat exchanger on the cooling loop of the diesel electric power plant, so they do not need to be considered when heating the community. The community center model simulation will be run for the conditions of Unalakleet for the sake of creating a flexible model.

2.3 Wind Resources

Generally, areas with average wind speeds of 6 m/s or higher at 10 m elevation are considered good candidates for wind power. Wind is classified by NREL based on average wind speed ranges as listed in Table 2 [4].

Table 2: Classes of Wind Regimes

Wind Power class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m^2)	**Speed m/s (mph)**	**Wind Power Density (W/m^2)**	**Speed m/s (mph)**
1	0	0	0	0
2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (16.8)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)
	1000	9.4 (21.1)	2000	11.9 (26.6)

Kongiginak and Unalakleet are both strong candidates for wind energy, as they have average annual wind speeds of 7.9 m/s and 7.7 m/s, respectively, at 50 m tower heights. This classifies both communities as Class 6 wind sites based on average wind speed data collected from 1978-2004 [3].

2.3.1 Kongiganak Wind Resources

Figure 10 shows the monthly average wind speeds for Kongiganak as determined from averages of years 1978-2004 [4]. From this data, we find that the average wind speed in Kongiganak is 7.9 m/s, or 17.8 mph.

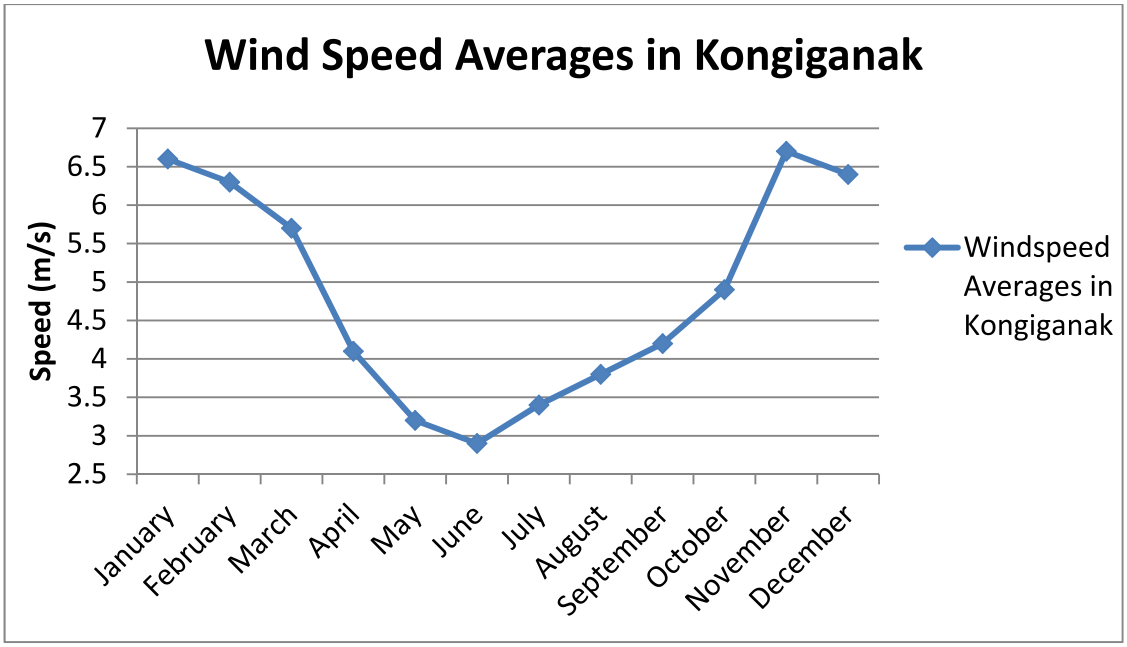

Figure 10: Monthly Average Wind Speeds in Kongiganak as Updated in 2004 [4]

2.3.2 Unalakleet Wind Resources

The Alaska Energy Authority gives the average windspeed in Unalakleet as 7.7 m/s, or 17.2 mph [14]. Figure 11 shows the monthly average wind speeds determined from averages of years 1978-2004 [19].

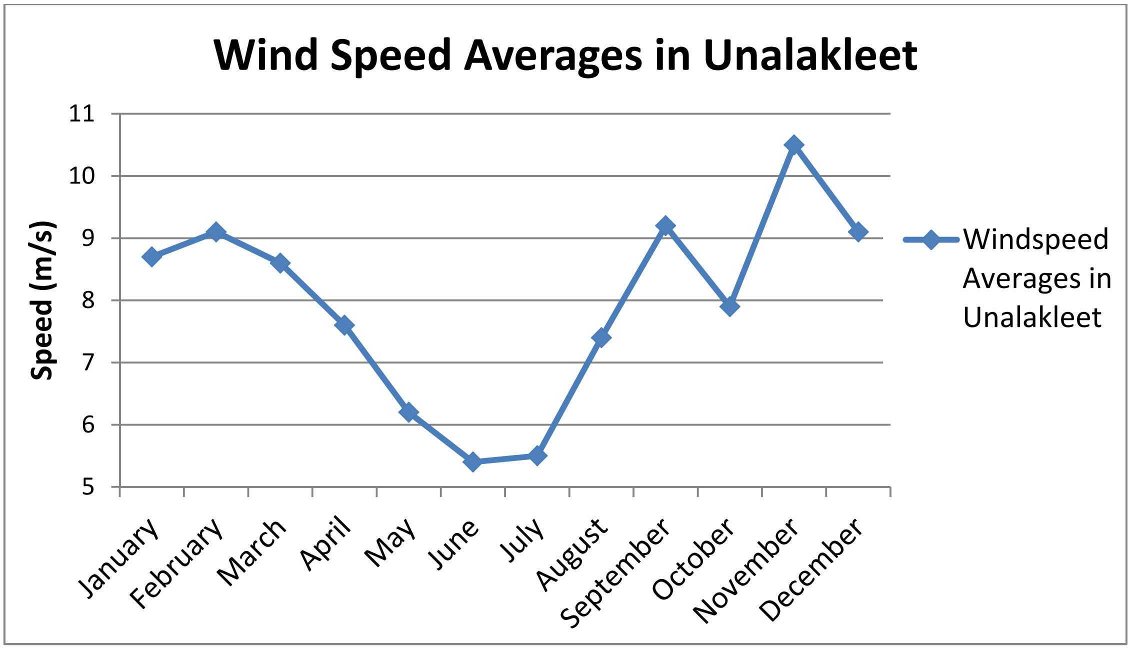

Figure 11: Monthly Average Wind Speeds in Unalakleet, as Updated in 2004 [19]

2.3.3 Weibull Distribution

When taking measurements of the wind speed, average velocities are used: usually hourly, daily, or monthly averages. However, if one calculates power based on the average velocity, the power generated will be underestimated because power is proportional to the velocity cubed and the average velocity is dependent on the amount of time the wind speed is at that average velocity value [8]. In order to accurately evaluate an area's wind speed potential, the amount of the time the wind speed is at each velocity value is determined using a Weibull distribution of the velocity.

The expression that characterizes the wind speed statistics is the Weibull probability density function in Equation 2.14

$$f(v) = \frac{\kappa}{c}\left(\frac{v}{c}\right)^{\kappa-i} exp\left[-\left(\frac{v}{c}\right)^{\kappa}\right] \tag{2.14}$$

where κ is the shape parameter and c is the scale parameter which characterizes the distribution. The value of c can be calculated from the overall average velocity using Equation 2.15.

$$c = \frac{2}{\sqrt{\pi}}\bar{v} \cong 1.128\bar{v} \tag{2.15}$$

The histograms and probability density functions plotted for Kongiganak and Unalakleet in the following sections show how the wind speed can be modeled closely with a Weibull distribution function.

2.3.3.1 Weibull Distribution for Wind Speed in Kongiganak

The Weibull distribution for the windspeed in Kongiganak in 2009 is given in Figure 12. The scale parameter is c = 9.395 and the shape parameter κ = 2.267.

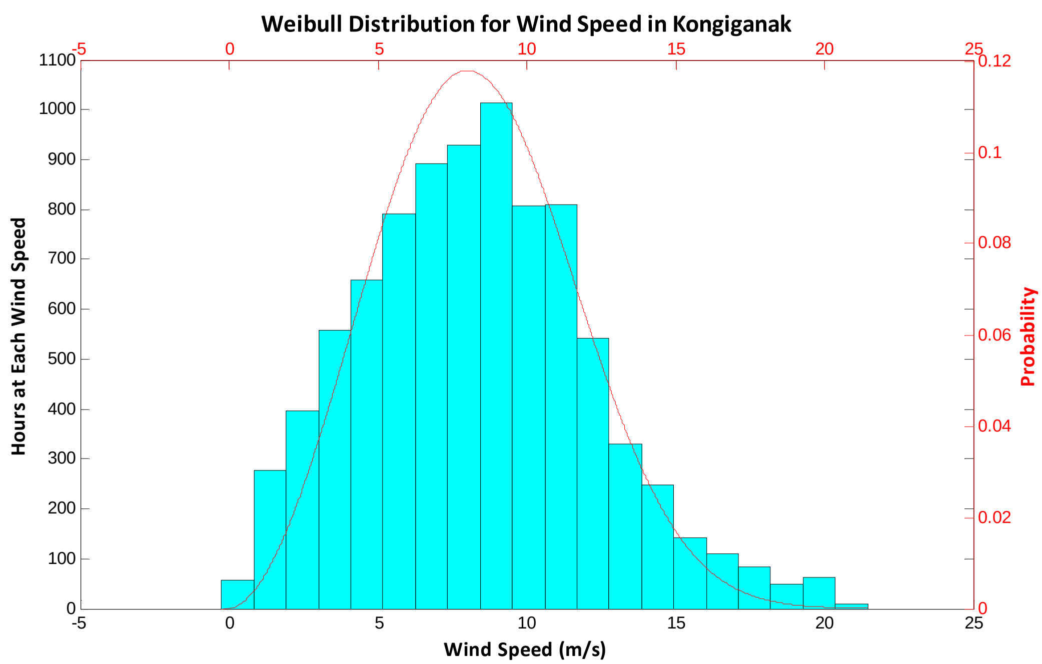

Figure 12: Weibull Probability Density Function and Wind Speed Histogram for Kongiganak in 2009 [14]

2.3.3.2 Weibull Distribution for Wind Speed in Unalakleet

The Weibull distribution for the wind speed in Unalakleet for 2011 is given in Figure 13. It has a scale parameter c = 8.686 and a shape parameter κ = 1.883.

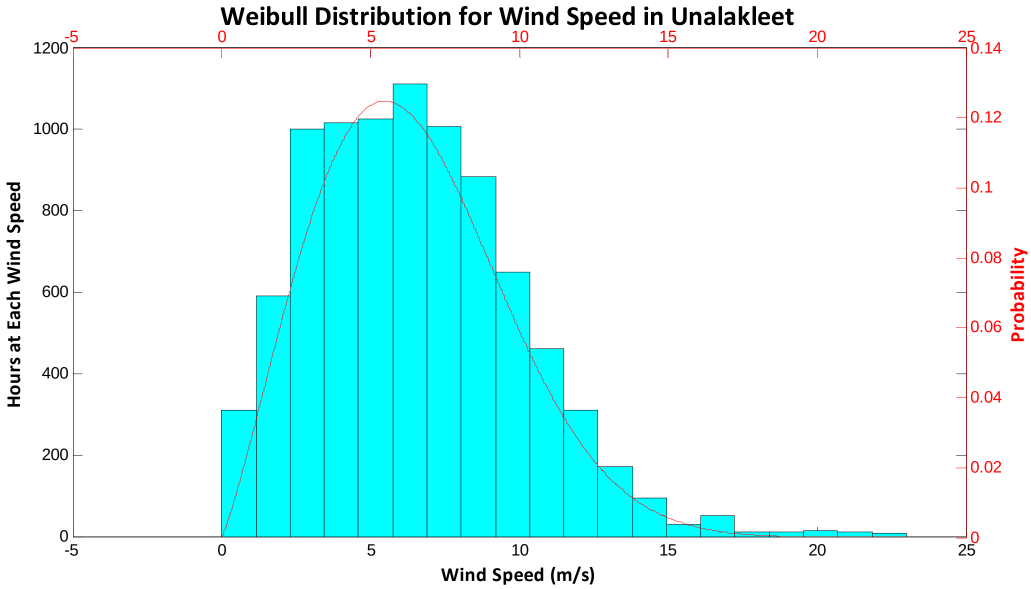

Figure 13: Weibull Probability Density Function and Wind Speed Histogram for Unalakleet in 2011 [6]

2.3.4 Wind Power

The power of the wind to turn the turbine blades at a given wind speed is generally described by Equation 2.17 [7]

$$P_w = \left(\frac{1}{2}\right) \rho\, A\, v^3 \tag{2.17}$$

where P_w is the power in the wind, ρ is the air density, about 1.225 kg/m^3 at 60 °F, which is the temperature at which the manufacturers measure the wind turbine's efficiency and output. It is used for all models as changing the density in accordance with the air temperature would over-complicate the model. A is the swept cross-sectional area normal to the velocity (m^2), and v is the velocity (m/s). The swept cross-sectional area normal to the velocity is given by Equation 2.18 as

$$A = \left(\frac{\pi}{4}\right) D^2 \tag{2.18}$$

where D is the diameter of the spinning turbine blade.

2.4 Electrical Power Resources

Electricity generated in excess of the demand from both wind turbines and diesel electric generators, can be converted to heat as a dump load to be used immediately or stored. However, it is more economical to dump excess electricity from wind than from diesel electric generators due to the lower COE from wind power than from diesel electric generation.

2.4.1 Kongiganak

Electric power in Kongiganak comes from four diesel electric generators and five 95 kWe Windmatic 17S wind turbine generators. The four diesel electric generators are a 235 kWe John Deere 6125, two 190 kWe John Deere 6081s, and a 140 kWe John Deere 6081. The five Windmatic 17-S wind turbines have a cut-in wind speed of 3.5 m/s, a cut-out wind speed at 25 m/s, and a wind speed for rated output power of 15 m/s. The rated output power of each wind turbine generator is 95 kWe at 480 VAC and 60 Hz [2].

2.4.2 Unalakleet

Electric power in Unalakleet comes from four 475 kW diesel electric generators (two as backups) and six 100 kWe Northwind 100B wind turbine generators. The six Northwind 100B wind turbines, which, like Kongiganak's Windmatics, have a cut-in wind speed of 3.5 m/s, a cut-out at 25 m/s, and a wind speed for rated output power of 15 m/s. The rated output power of each wind turbine generator is 100 kWe at 480 VAC and 60 Hz [8].

2.5 Ambient Temperature Profiles

2.5.1 Temperature in Kongiganak

The seasonal high temperature for Kongiganak is 70 °F, with a low of -28 °F. The annual mean is 31.9 °F. The annual temperature plot for 2009 based on daily averages is given in Figure 14.

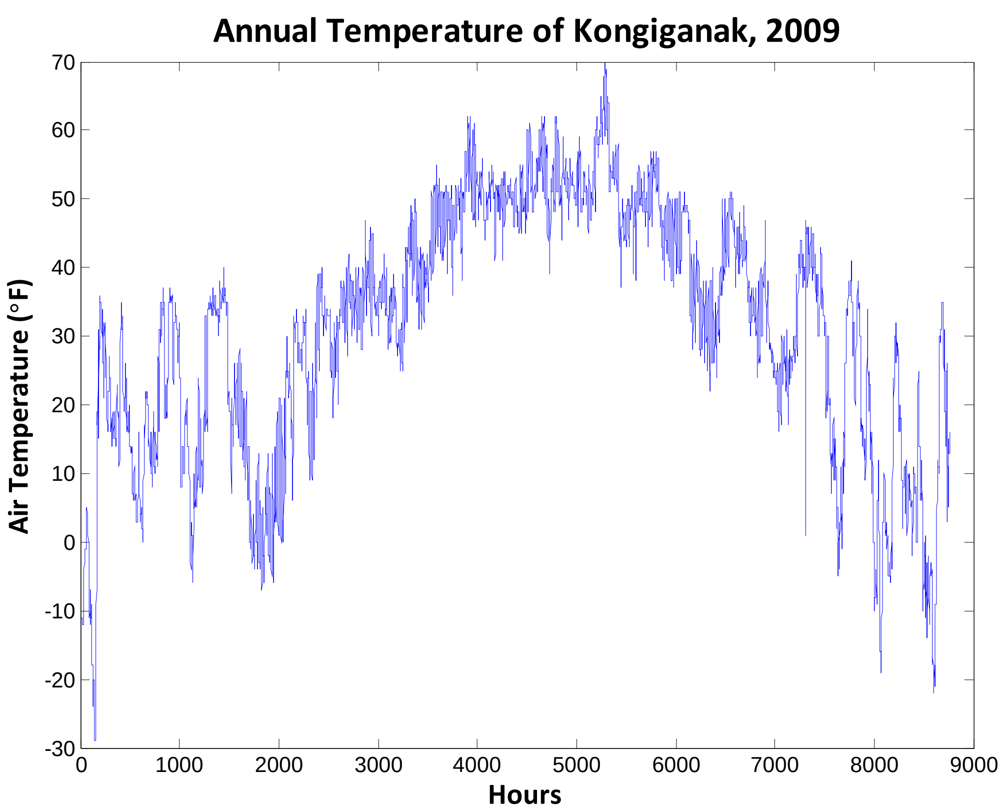

Figure 14: Kongiganak Annual Outside Temperature (2009) [2]

2.5.2 Temperature in Unalakleet

The seasonal high temperature for Unalakleet is 72 °F, with a low of -33 °F. The mean is 28.1 °F. The annual temperature plot for 2011 based on daily averages is given in Figure 15.

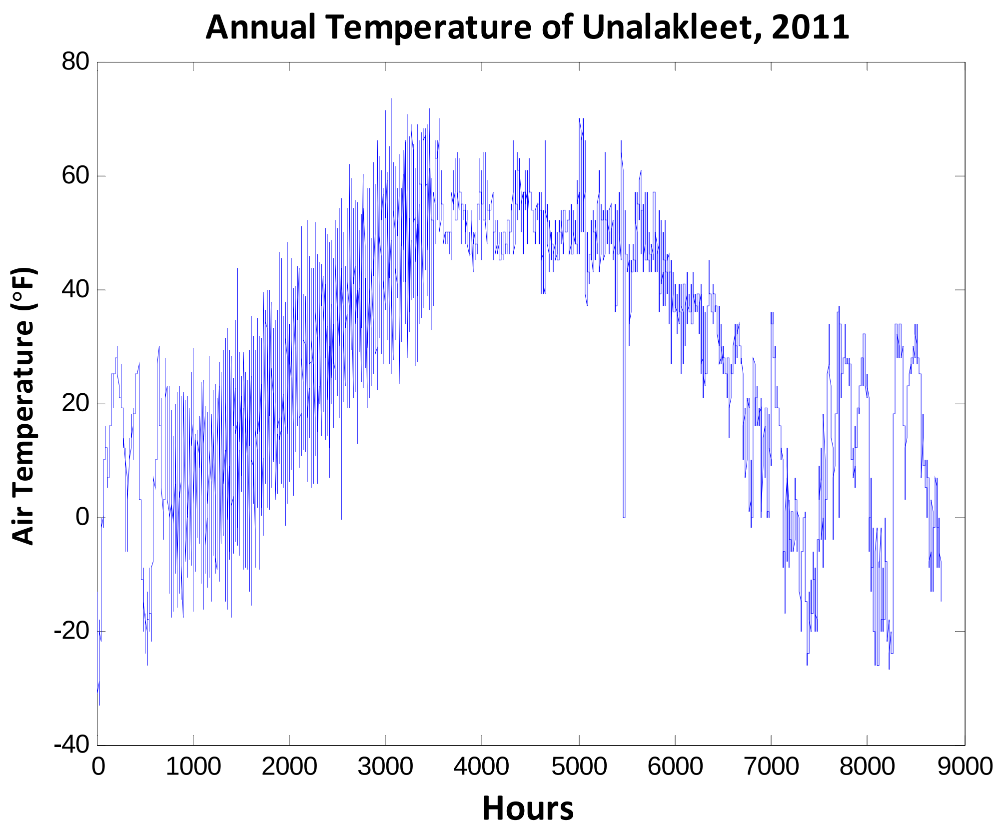

Figure 15: Unalakleet Annual Outside Temperature (2011) [6]

2.6 Parameters Used for Economic Evaluation

Once the heater, building, and wind resource models have been created and the simulation cases have been performed, various metrics must be used to evaluate the economic feasibility of the system. These include investment rate, inflation rate, and discount rate.

2.6.1 Investment Rate, Inflation Rate, and Discount Rate

The investment rate is the percentage rate at which the value of money increases every year. Inflation rate is the rate prices and interest rates increase over time. Inflation rate takes into account the future price rise in the project commodities including fuel and different power system components. Discount rate is the difference between the investment rate and the inflation rate. Discount rate, as given in Equation 2.19, is generally used in life cycle cost analysis calculations [15].

$$\text{Discount Rate} = \text{Investment Rate} - \text{Inflation Rate} \tag{2.19}$$

The life cycle is the life time of the project. It is the time at the end of which the system components require replacement.

2.6.2 Net Present Value

The net present value (NPV) is the money that will be spent in the future discounted to today's money. The NPV plays an important role in deciding the type of the system to be installed. The NPV of a system is used to calculate the total spending on the installation, maintenance, replacement, and fuel cost for the type of system over the life cycle of the project. Knowing the NPV of different systems, the user can install a system with minimum NPV. NPV can be calculated as Equation 2.20 [10]

$$P = \frac{A[1-(1+i)^{-n}]}{i} \tag{2.20}$$

where P is the present worth, i is the discount rate, n is the year in which the money will be spent, and A is the annual sum of money. NPV is sometimes described based on the capital recovery factor (CRF), or $\frac{A}{P}$ according to Equation 2.21 [10].

$$CRF = \frac{A}{P} = \frac{i}{[1-(1+i)^{-n}]} \tag{2.21}$$

Generally, a higher NPV is better due to a higher rate of return on the initial investment. However, the economic analysis in this project seeks for a lower NPV, and therefore, a lower cost of energy (COE) based on the current value of displaced heating oil and the value of the wind energy displacing it during a fairly short (20 year) life cycle.

2.6.4 Payback Period

Payback period is the time required to recover the total extra money invested in a project. It is given according to Equation 2.22 [10].

$$Payback\ Period = \frac{Extra\ Investment}{Rate\ of\ Return} \tag{2.22}$$

Payback period is the major deciding factor for the economic feasibility of a project. If the payback period of the system is less than the life cycle of the system, the project is economically feasible. However, much shorter payback periods than those calculated from Equation 2.20 are often times expected from energy project financers making it difficult to implement projects. This is why it is also necessary to consider the future cost of energy in determining the feasibility of an energy project.

2.6.5 Cost of Energy

To determine whether it makes economic sense to install new facilities, the cost of electricity (COE) is determined by Equation 2.23 [10]

$$COE = \frac{Total\ Annual\ Spending}{Energy\ to\ the\ Load} \tag{2.23}$$

where the Total Annual Spending (USD) is the sum of yearly expenses associated with the entire system, and the Energy to the Load (kWh) is the energy generated by all means.

2.7 Summary of Heat and Energy Transfer Model Theory

The theories of energy transfer described in Section 2.1 are employed in Chapter 3 to develop thermal models using masonry ETH for the buildings described in Section 2. Inputs to the model are the wind speed, available wind generation, and ambient temperature as described in Sections 2.3-2.5. The economic analysis tools described in Section 2.6 are used to determine the economic feasibility of masonry ETH.

Chapter 3: Modeling and Verification of Masonry ETH in Simulink®

The goal of modeling ETH systems for Alaska wind-diesel microgrids is to create the optimal system through the best use of available resources. The best solution is inexpensive, reduces the use of diesel fuels, and is well-liked by the village. This is determined by analyzing several heating options for the village, calculating the costs of installation and maintenance, and comparing costs to savings in fuel at various fuel prices. This is called a sensitivity analysis, and will be used to evaluate the economic benefit in Chapter 4.

An important goal of this ETH model is for it to be adaptable to any community building and heating/storage scenario. It should only require slight modifications to work for different communities with different numbers of buildings, wind turbines, wind profiles, and seasonal temperature variations.

3.1 House Thermal Energy Model

Because different buildings have different sizes, levels of insulation and heating demands, several types of buildings will be modeled under various scenarios. In general, thermal energy enters a house through the heater, both from the thermostat switching on the heat by demand as well as from losses from the heater and leaves the house through the insulation. The overall system is described by Equations 2.1, 2.4, 2.6, and 2.8.

In simulations that include houses, heaters, and energy losses, the portion of the model for the house that is used is shown in Figure 16. The system regulates when wind generators are employed.

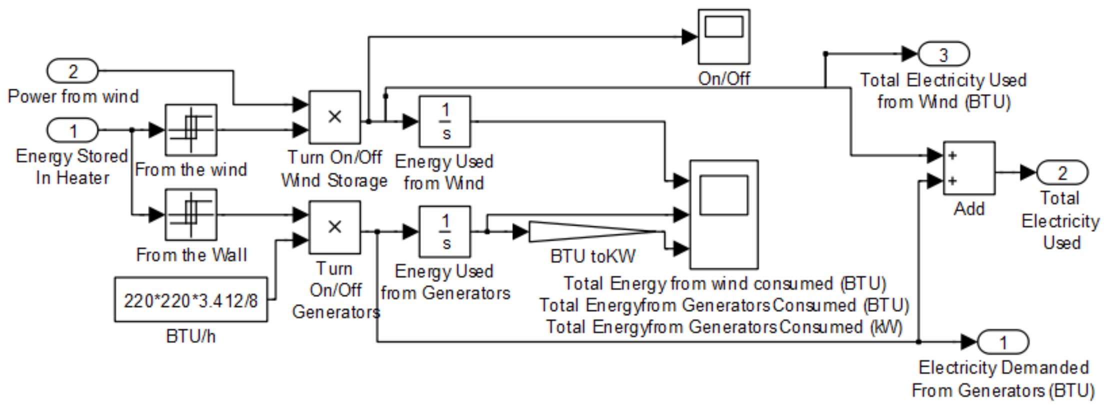

Figure 16: Single House Simulink® Model

Figure 16 shows the portion of the model that triages the source of the energy to charge the Steffes unit. When the Steffes is not fully charged, the energy from the wind is turned on. When the Steffes is completely discharged, and when the thermostat turns on the heat, and no wind is available, the energy is modeled to come from the generators.

Another portion of the Simulink® model is shown in Figure 17. This portion of the model uses one input (outside temperature, given from a file) and the house temperature, which is determined by Equation 2.1. A feedback loop updates the house temperature at the output, bringing it to the input.

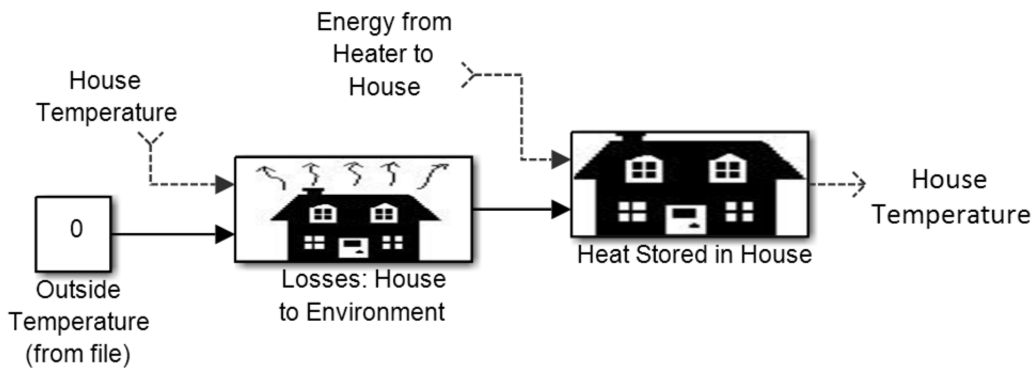

Figure 17: Simulink® Model of the House (or Other Building)

The formula under the mask of ‘Heat Stored in House’ is shown in Figure 18 from Equation 2.11, where the ‘Gain1’ block converts from hours to minutes, and the ‘dT/dt1’ value 351.3938 is the product of mass times heat capacity, where the volume of air of is 6,000ft^3, density is 0.24402 lb/ft^3, and heat capacity is 0.24 BTU/lb$_m$°F, at room temperature and pressure [9].

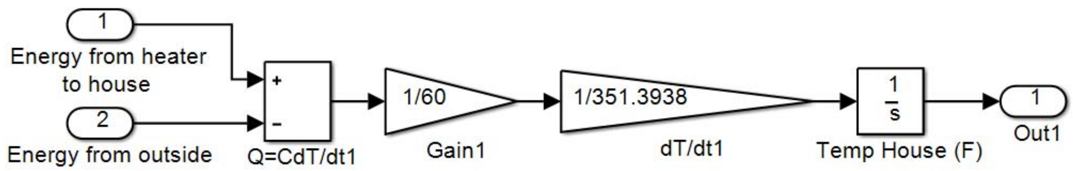

Figure 18: ‘Heat Stored in House’ Model

The mask ‘Losses: House to Environment’ is shown in Figure 19, and is derived from Equation 2.6, where 2200 is the volume of a small house in ft^3, and 20 is the R-value of the house.

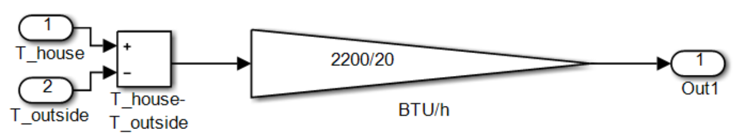

Figure 19: Losses: House to Environment

The mask ‘Heater Losses’ is shown in Figure 20, and is derived from Equation 2.7, where ‘BTU/h’ is 1/R$_{therm}$ with a R$_{therm}$ value of 0.4146°F-h/BTU.

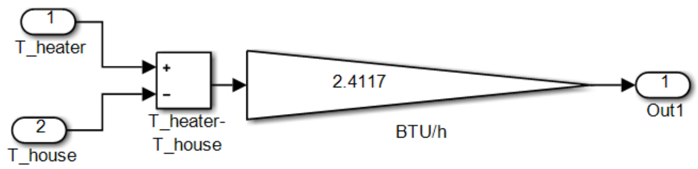

Figure 20: Heater Losses

3.2 Oil Heater Model

Currently, oil heaters are used to heat residences. Burning oil is one of the most efficient ways to heat a domestic space, compared with using electric heat and burning wood. Using a model to determine the quantity of oil required, and subsequently its cost will help determine whether it is economically viable to invest capital into installing and maintaining electric heaters or continuing to use oil stoves. Figure 21 shows the model of an oil heater. When the thermostat indicates that the temperature of the house is 1 °F (or more) below the desired temperature, the heater is turned on, releasing 20,000 BTU/h to the room. When the temperature is 4 °F above the set point, the heater is turned off. This corresponds with Toyo's manufacturer specifications [21].

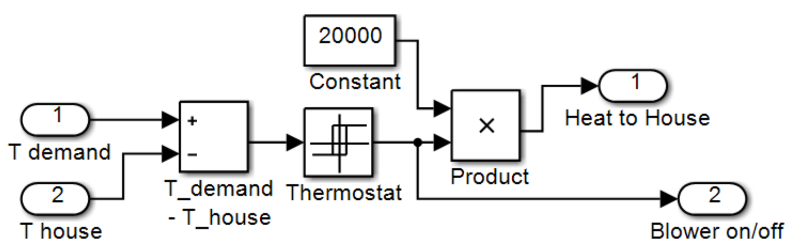

Figure 21: Oil Heater Model

The goal of modeling the oil heater is to determine the price of heating a home with only oil, heating a home with oil and a Steffes unit (powered only by excess wind), and heating a home with only a Steffes unit (powered by excess wind and the diesel electric generators).

3.3 Steffes Heater Model

Steffes heaters take electricity from an electric generation source and convert it into heat energy through resistive elements, which is stored in masonry bricks. A thermostat turns on a fan to blow air across the bricks. The model of the Steffes heater charging with no thermal losses is shown in Figure 22.

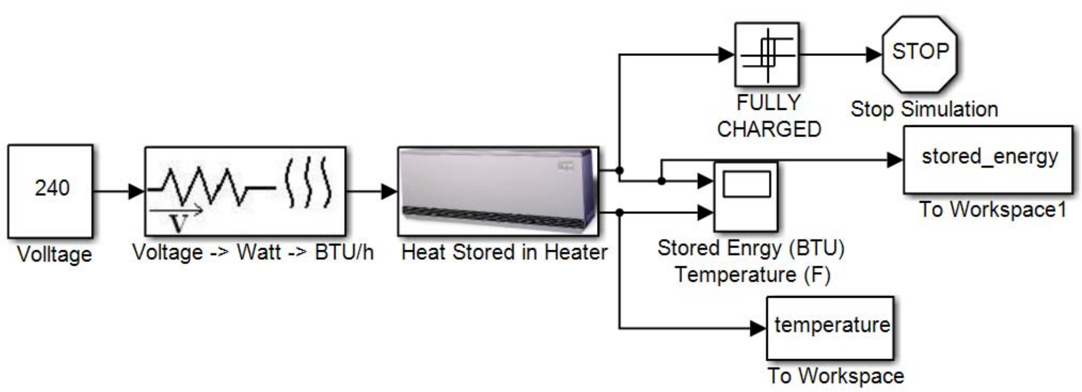

Figure 22: Steffes Heater Model with Constant Charging of Masonry Bricks with No Thermal Losses

The mask for the conversion of voltage to heat is given in Figure 23 and governed by Equation 2.2, using a factor of 3.412 to convert watts to BTU/h.

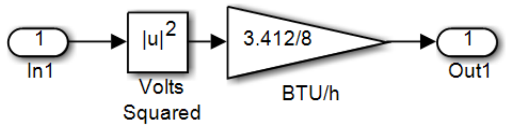

Figure 23: Voltage->Watt-> BTU/h Conversion

The mask for the 'Heat Stored in Heater' block is shown in Figure 24, which is derived from Equation 2.10.

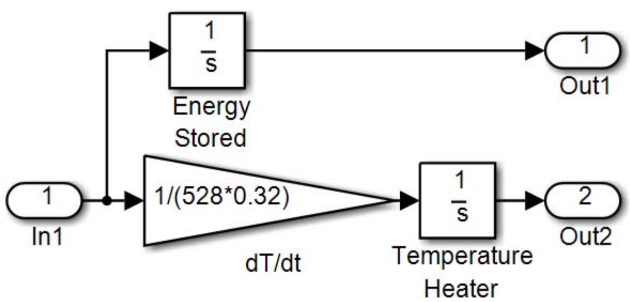

Figure 24: 'Heat Stored in Heater' Submask

In modeling the brick storage system, it is useful to model the heater-house system as a heater and house storing energy as heat, and thermal energy leaving the house. Because thermal storage of heat energy in large masses at high temperatures involves heat loss from the storage mass to the environment, it is important to model this as a consequence of thermal storage. Equation 2.3 becomes more specific in Equation 3.1

$$Q = C\frac{dT_{heater}}{dt} = \frac{(V(t))^2}{R}\,3.412 - \frac{SA}{R_{therm}}(T_{Heater}(t) - T_{in}) - \tag{3.1}$$

$$20{,}000\text{ BTU/h } kA\frac{T_{heater}-T_{house}}{thickness}$$

where all variables are described in Table 3.

The energy system of the house is modeled as heat from the heater minus losses to the outside as given by Equation 3.2.

$$Q = m_{air}C_{air}\frac{dT_{in}}{dt} = 20{,}000\text{ BTU/h} - \frac{SA}{R_{therm}}\left(T_{in}(t) - T_{outside}\right) \qquad (3.2)$$

For these calculations, m_{air} is determined by the density of air at room temperature multiplied by the volume of the empty house. As was the case in Equation 2.11, this is a simplification that treats the house as a mass of still air, and its implications are expounded upon in section 5.4. The variables of Equations 3.1 and 3.2, as well as their description and numerical values for this system, are given in Table 3.

Table 3: Values and Variables Used in Equations 3.1 and 3.2 [9]

Variable	**Description**	**Value/Units**
Q	Heat	BTU
C	Heat Capacity	168.96 BTU/°F-h
T_{heater}	Heater Temperature	°F
C_{air}	Heat Capacity of Air	0.24 BTU/°F-h
ρ	Density of Room Temperature Air	0.2442lb/ft^3
T	Time	Hours
C_p	Specific Heat	0.32 BTU/(°F-lb-h)
R	Electric Resistance	8 Ω
SA	Surface Area	3844 in^2
R_{therm}	Thermal Resistance	4.147 °F-h-ft^2 /BTU
T_{out}	Outside Temperature	90 °F
T_{in}	Inside Temperature	60 °F
W to BTU/h	Converting Watts to BTU/h	1 Watt = 3.4121 BTU/h

3.3.1 Modeling the Daily Temperature Demand

Thermostats can be programmed so that the temperature is lower when a household's occupants are sleeping or at work during the day. Each 24 hour cycle of temperature demand is given in Table 4 and Figure 25.

Table 4: Daily Temperature Demand

Time	Temperature
00:01-06:00	60 (°F)
06:01-0:900	65 (°F)
09:01-13:00	60 (°F)
13:01-21:00	65 (°F)
21:01-0:00	60 (°F)

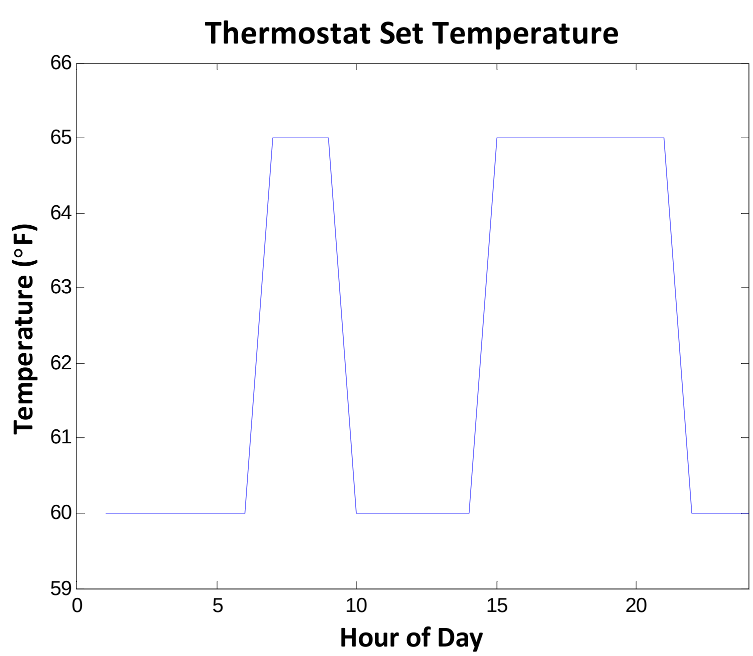

Figure 25: Daily House Temperature Demand

3.4 Modeling Electric Generation Sources

If it is not possible to heat a house exclusively with excess wind energy, then a secondary source must be used. That secondary source is either heat from burning heating oil in a Toyo stove or electric power from diesel generators to the Steffes. Diesel generators are modeled to provide 240 VAC of electricity from the microgrid (using the “From the Wall” switch, as shown in Figure 16), whenever the Steffes is empty and heat is demanded. Diesel generators generally operate at 40% efficiency, or 82,011 BTU/gal [13].

3.5 Wind Turbines

The relationship for converting wind speed to power is given by Equation 2.17 [7]

$$P_w = \left(\frac{1}{2}\right)\rho\, A\, v^3 \tag{2.17}$$

multiplied by an efficiency η=0.25, with a diameter d=17ft as given in the manufacturer’. It is modeled in Simulink® according to Figure 26.

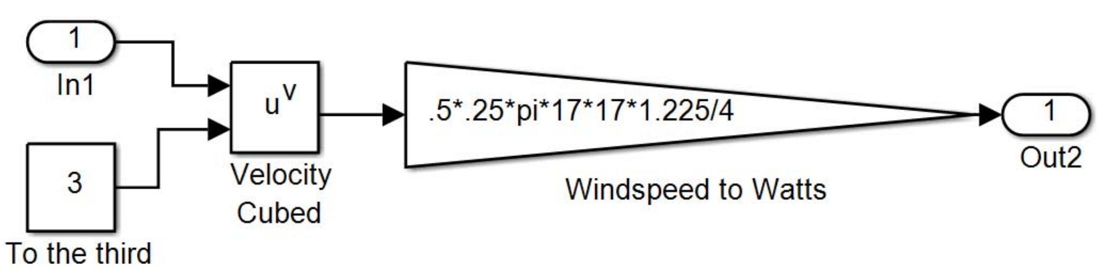

Figure 26: Wind Turbine Model

This model takes wind speed as an input, and outputs the power produced. It is used in every model where wind speed is converted to power.

3.6 Modeling Systems

The Steffes heater charges at a rate proportional to the voltage input, and releases stored heat energy at a rate dependent upon the thermal demand (if any), and the temperature difference between the heater and room. Several test cases are created so that it is possible to analyze the operation of the Steffes unit under different conditions, to best apply the Steffes to various heating situations.

3.6.1 Heater Loses Heat to House of Constant Temperature

Figure 27 shows the model of a charging heater losing heat to a house of constant temperature.

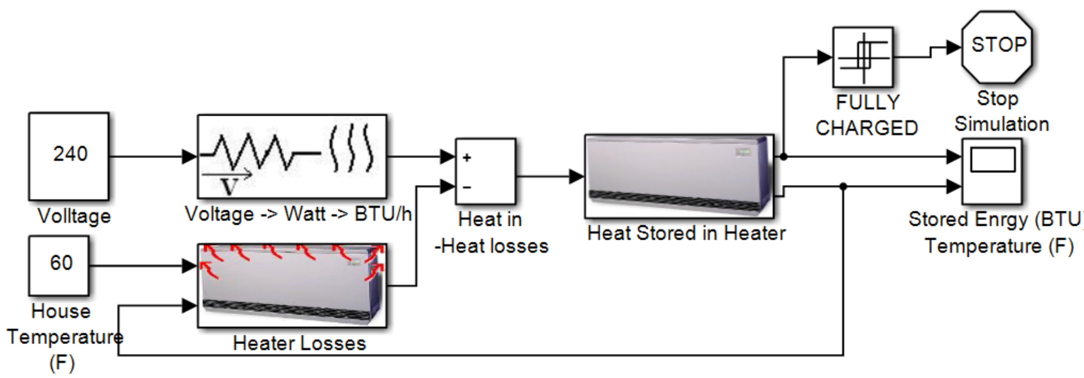

Figure 27: Model of Charging Heater Losing Heat to House of Constant Temperature

This model shows that stored energy is simply a function of electrothermal energy in minus the insulated losses from the heater. The temperature of the heater is a function of the heat stored in the heater. Figure 28 shows a graph of the bricks charging, modeled as a lossless system receiving a constant voltage (240 VAC according to the manual). The bricks store 136,480 BTU in 5.55 hours, resulting in a temperature increase of 807.78 °F. The graph's constant, positive slope illustrates the increase in energy and temperature.

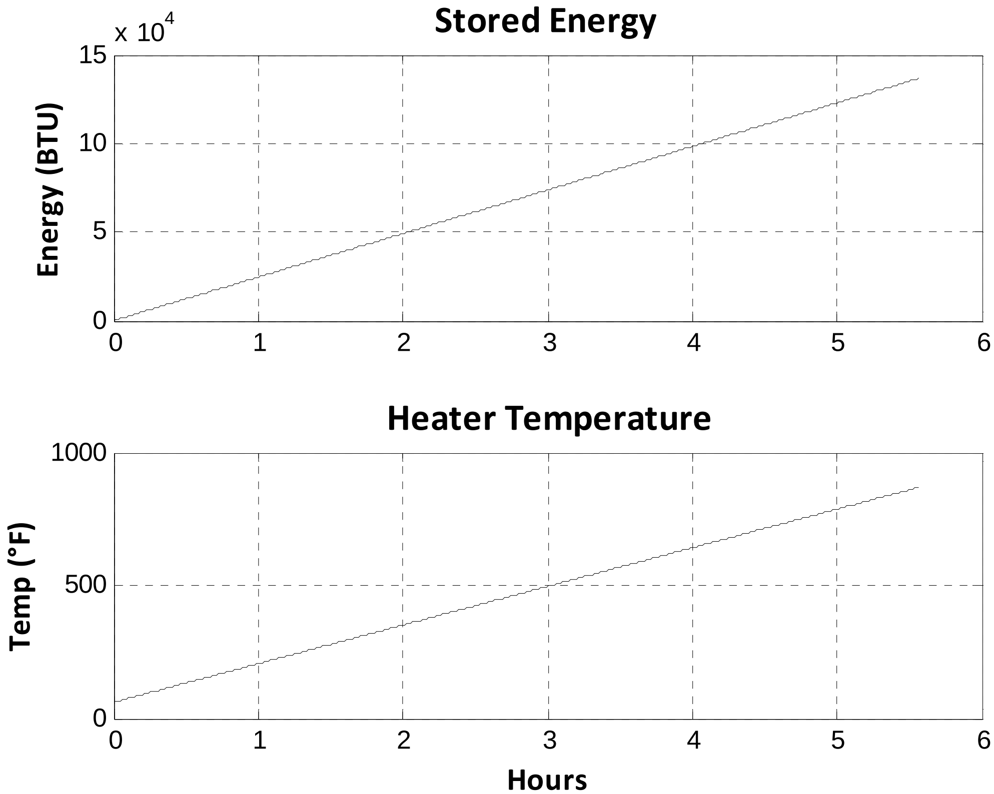

Figure 28: Stored Energy (BTU), and Heater Temperature (°F) When Charging the Steffes Unit in a Lossless Environment (Full Charge in 5.55 hours)

3.6.2 Heater Loses Heat to Perfectly Insulated House

Figure 29 shows a model of a charging heater losing heat to a perfectly insulated small house, allowing the temperature of the house to increase.

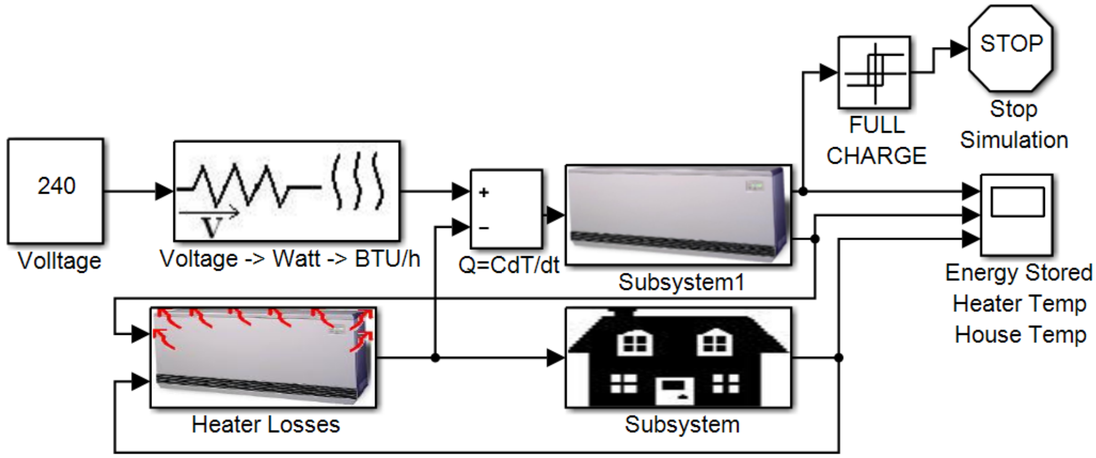

Figure 29: Charging 60 °F Heater Losing Heat to a Perfectly Insulated 60 °F House

When the heater is charged with a constant voltage of 240 VAC to a 60 °F house which is modeled to lose no heat to the outside, but only gain heat from the heater, it takes 5.79 hours to completely charge with the same temperature increase of $\Delta T = 807.78$ °F, as shown in Figure 30. The house temperature rises from 60 °F to 77 °F. Energy is transferred at a rate of 23,600 BTU/h. This is 4.14% longer than it takes to charge a lossless system, which makes sense considering the fact that as the heater temperature increases relative to the room, the heater loses energy to the room more slowly, at an average rate of 1776 BTU/h, according to Equation 2.6.

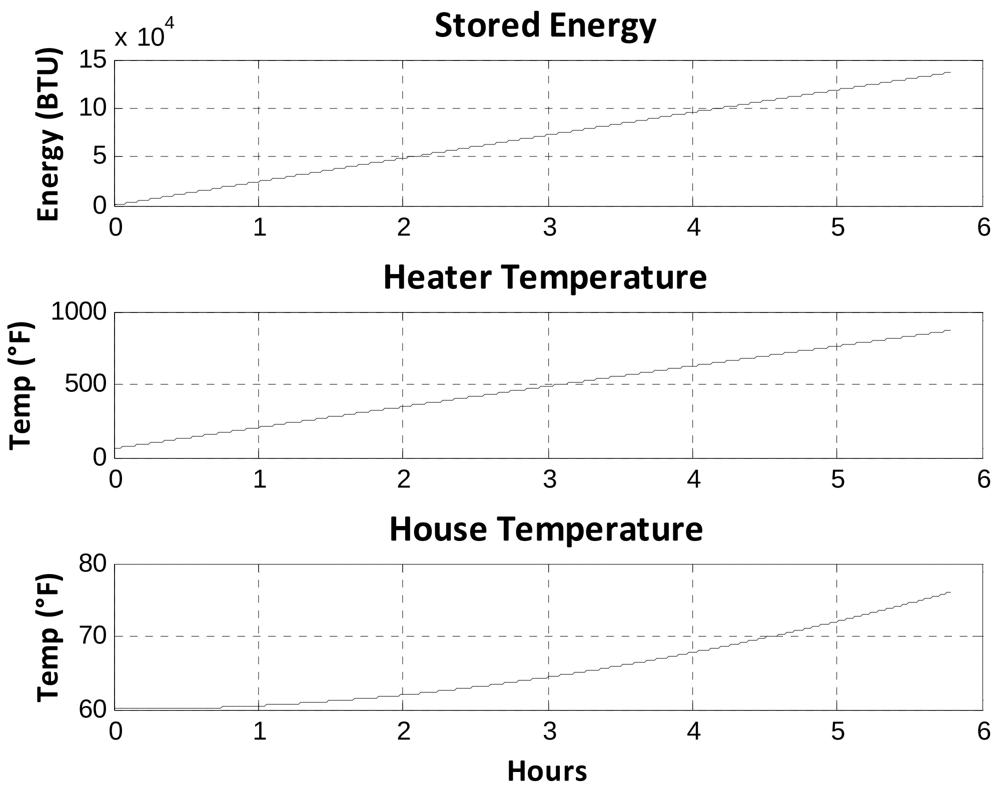

Figure 30: Charging the Steffes Unit in a Lossy Environment (Full Charge in 5.79 Hours): Energy Stored (BTU), Heater Temperature (°F), House Temperature (°F)

3.6.3 Heater in Very Lossy Environment

Figure 31 shows a heater discharging to a 60 °F small house, which loses heat to the outside at 0 °F. There is no thermostat.

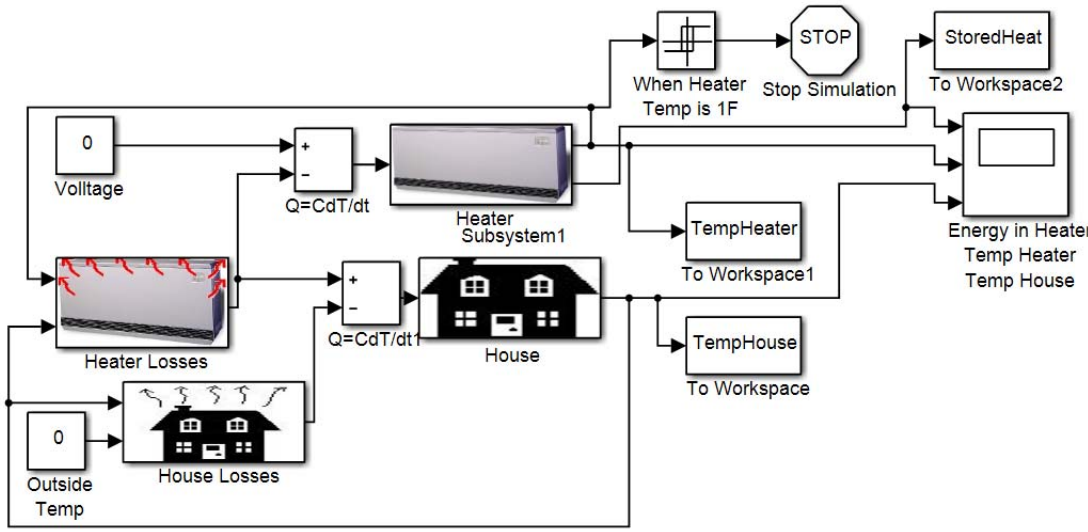

Figure 31: Discharging a Steffes Heater in a Very Lossy Environment

This model builds upon Figure 29, and additionally takes into account that energy from the house is lost to the outside. Therefore, the energy stored in the house is the energy from the heater losing energy, minus the energy that is lost from the house. When the 867 °F heater storing 136,480 BTU is discharged to a 60 °F house, the heater depletes its stored energy after 192 hours, and continues to deplete energy as the temperature of the house drops while the house loses energy to the outside. This is shown in Figure 32.

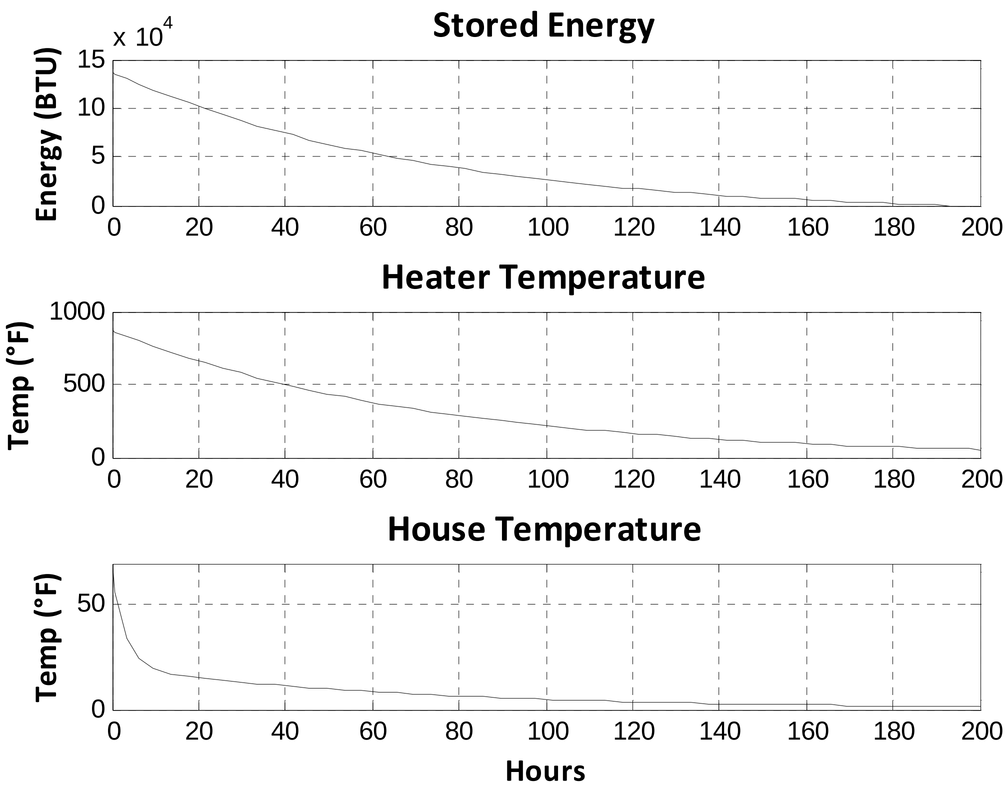

Figure 32: Discharging a Steffes Unit in a Lossy 60 °F House (Stored Energy Decays Toward Zero BTU in About 500 hours): Energy Stored (BTU), Heater Temperature (°F), House Temperature (°F)

3.6.4 Steffes Heater (with Thermostat) Charging in a Very Lossy Environment

Figure 33 shows a thermostatically-controlled heater charging in a 60 °F small house, losing heat to the outside at 0 °F.

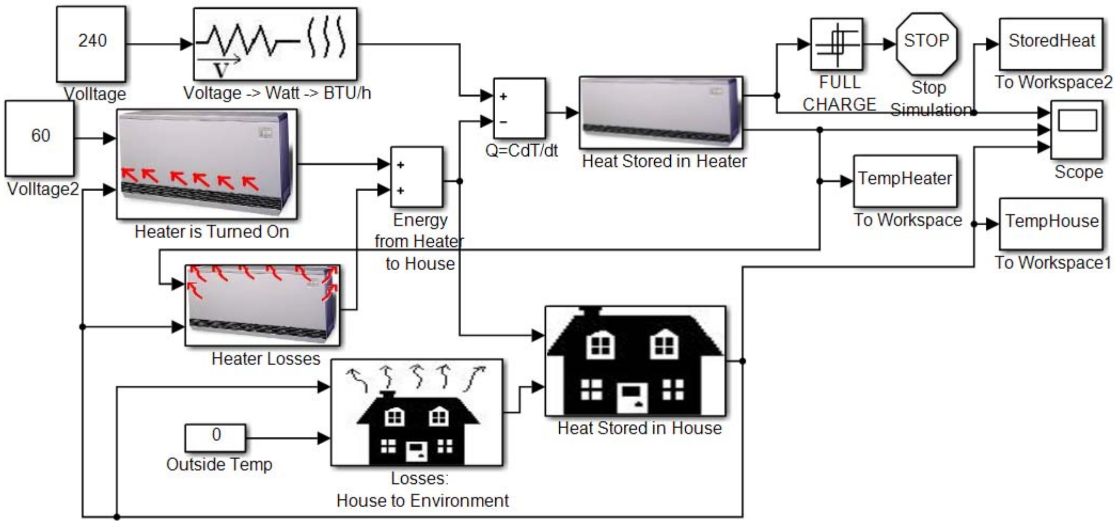

Figure 33: Charging a Steffes Heater in a Very Lossy Environment

Figure 34 shows the response of the thermostatically-controlled heater. The heater takes 7.6 hours to charge, turning on 70 times in the process. It is reasonable that it took longer to charge the heater when the heater was releasing thermal energy into the room as demanded.

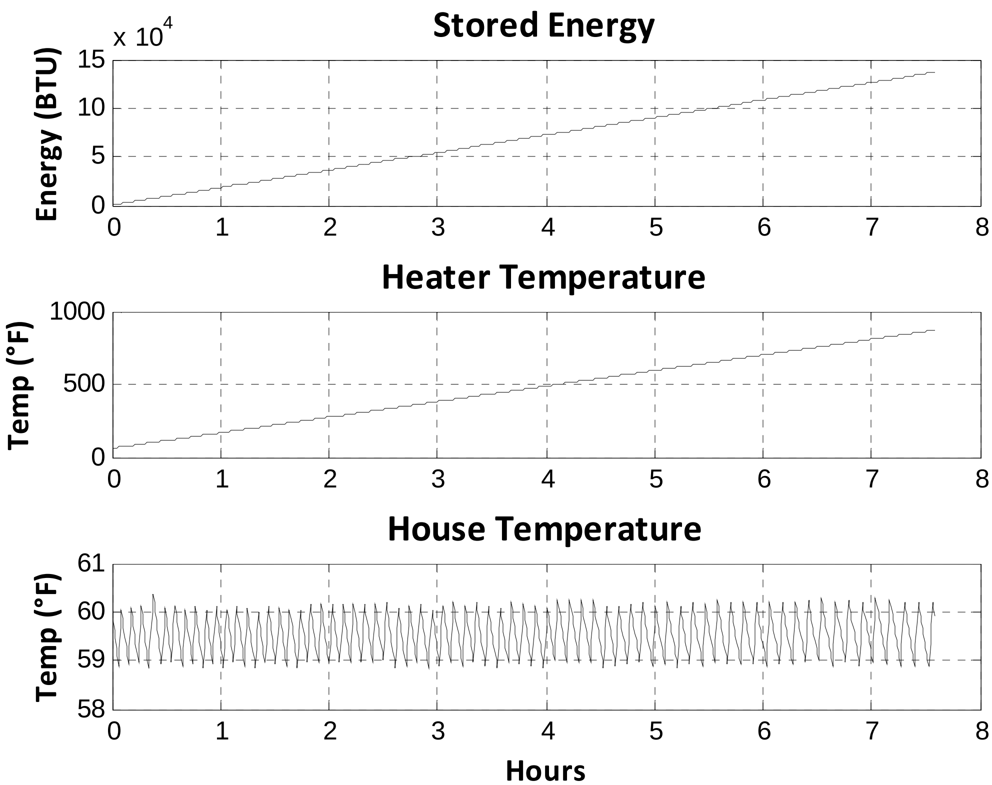

Figure 34: A Thermostatically-Controlled Steffes Charging in a Very Lossy Environment: Energy Stored (BTU), Heater Temperature (°F), House Temperature (°F)

3.6.5 Steffes Heater (with Thermostat) Discharging in a Very Lossy Environment

Figure 35 shows a fully charged heater, losing heat through insulation, and discharging heat through the blower as it is demanded.

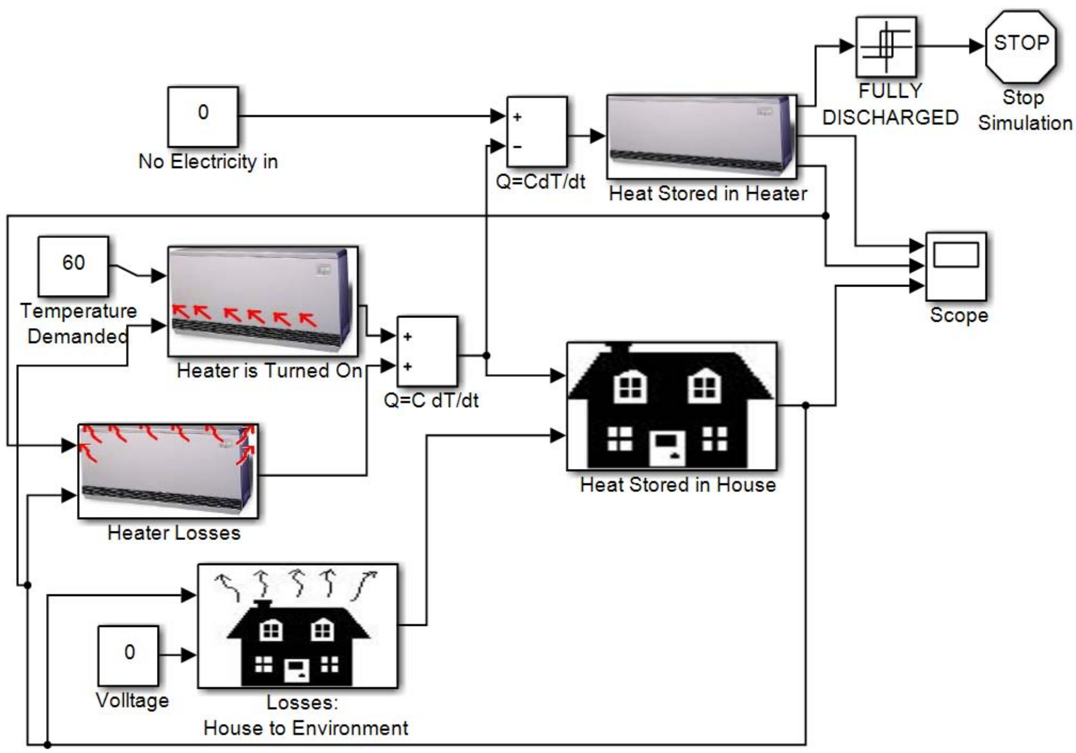

Figure 35: Steffes Heater (with Thermostat) Discharging in a Very Lossy Environment

Since the thermostatically controlled heater is discharging to a very lossy environment and is also fulfilling the thermal demand, it will take a shorter time to discharge than it would take to charge a house that is maintained at a constant temperature.

A fully charged thermostatically controlled heater (867 °F and 136,480 BTU) discharges to a lossy 68 °F room and a 0 °F outside environment in 21.2 hours. The thermostat activates the blower 29 times, approximately once every 44 minutes. When the thermostat turns the blower on, the heater loses 22,000 BTU/h to the room, and when it is off, it loses 2,000 BTU/h to the room. This is shown in Figure 36.

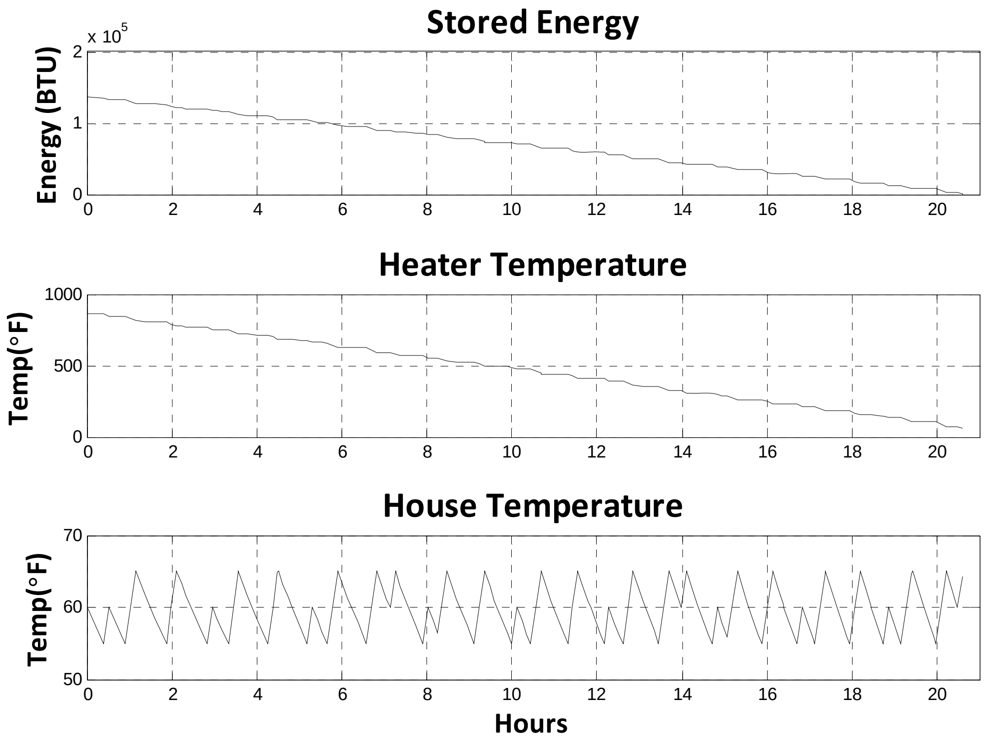

Figure 36: Thermostat Activates Blower Periodically as Steffes Discharges in a Lossy Environment: Energy Stored (BTU), Heater Temperature (°F), House Temperature (°F)

3.6.6 Thermostatically Controlled Heater Meets Thermal Demand for Year

Figure 37 models a thermostatically controlled heater in a small house for a year. A thermostatically controlled heater activates the electricity input when the heater is not storing any energy. A temperature charge controller switch turns on the heater when the heat is nearly depleted. This is similar to combining both the models of the heater charging and discharging.

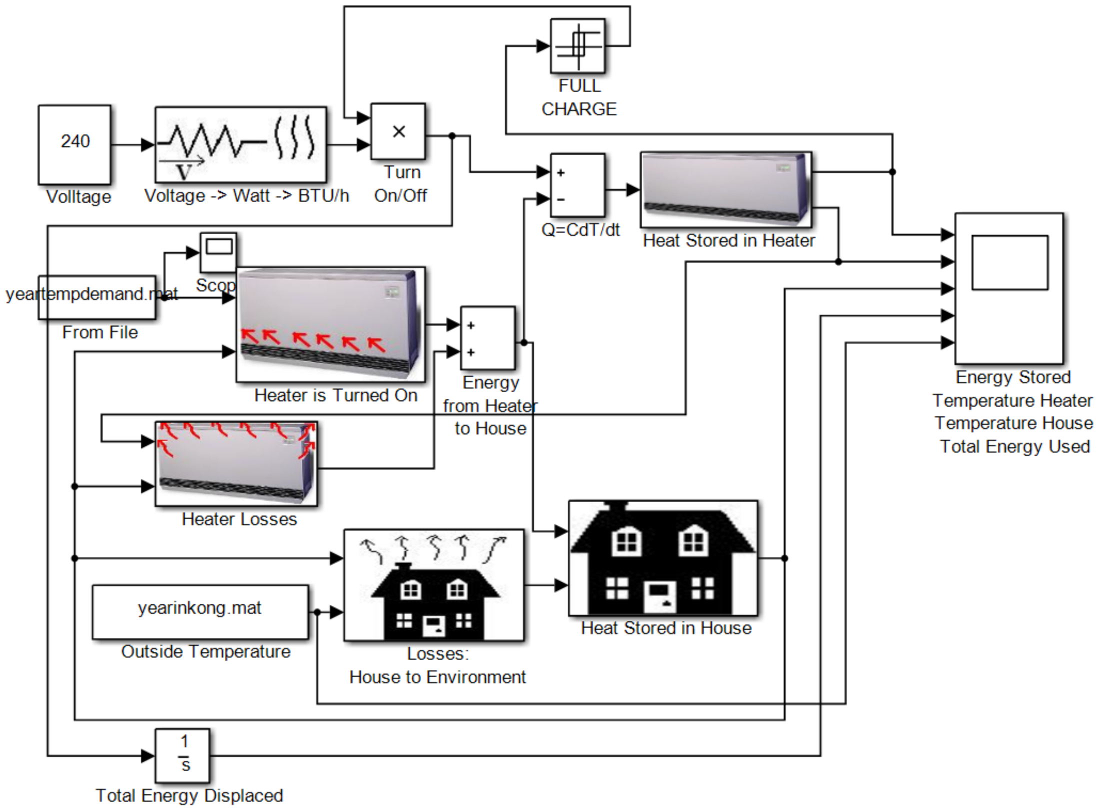

Figure 37: Thermostatically Controlled Model of a Small House for One Year

3.6.7 Small House

A small house, the size of a normal residential house, has a 20 ft × 30 ft footprint, a 10 ft ceiling, and an insulation value of R-20 in the walls. When the heater is charged with a constant voltage of 240 VAC, and loses energy to a 60 °F house, it takes 5.78 hours to fully charge, with a temperature increase of 867 °F. The house temperature rises from 60 °F to 76.1 °F.

When a 60 °F thermostatically controlled uncharged heater (tolerance of 5 °F) is turned on in a 60 °F room, and the outside temperature is 0 °F, the heater charges in 7.6 hours. A tolerance of 5 °F was chosen because it was specified by Toyo [20]. The heater turns on 11 times, or about once every 30 minutes, during this period. When the blower is on, the heater gains 5,000 BTU/h; when the blower is off, it gains 25,000 BTU/h.

When the fully charged heater (867 °F and 136,480 BTU) discharges to a perfectly insulated 68 °F house, the entire system reaches equilibrium at 500 hours (21.8 days), when the heater and room equilibrate to 117 °F. At this point the heater stores 9700 BTU.

A fully charged heater (867 °F and 136,480 BTU) in a 68 °F lossy house and a 0 °F outdoor environment (this simulates a generic winter village environment) discharges completely after 6.67 days when the heater is 92 °F and the room is 1°F. The heater continues to lose heat to the room which loses heat to the outside, approaching, but never reaching 0 °F. After 480 hours (20 days), the heater is 1 °F and the room is 0.01 °F.

A fully-charged thermostatically-controlled heater discharges to a 68 °F lossy house, with an outside temperature of 0 °F in 21 hours. The thermostat turns on 34 times, each time for approximately 20 minutes.

These results are summarized in Table 5.

Table 5: Time to Charge and Discharge Small House under Various Conditions (Hours)

Charging/ Discharging	Condition	Thermostat?	Time to Charge/ Discharge (hrs)
Charge	Lossless	No	5.78
Discharge	Lossless	No	N/A (>485)
Charge	Lossy House	No	7.6
Discharge	Lossy House	No	N/A (>500)
Charge	Lossy House	Yes	7.68
Discharge	Lossy House	Yes	21

The following two sections show results of annual simulations for small houses in Kongiganak and Unalakleet.

3.6.7.1 Small House in Kongiganak

The model for a small house in Kongiganak predicted that 27.4 MBTU of energy is required to heat the house using a Toyo stove as illustrated in Figure 38. Actual results show that a small house in Kongiganak requires 28.49 MBTU of heat for an entire year. This small (4.5%) difference can be accounted for by many factors, including failure to account for the contributions of human body heat, pets, and cooking heat to the house, an over-estimation of the wind accounted for in this model, and more efficient heating than expected.

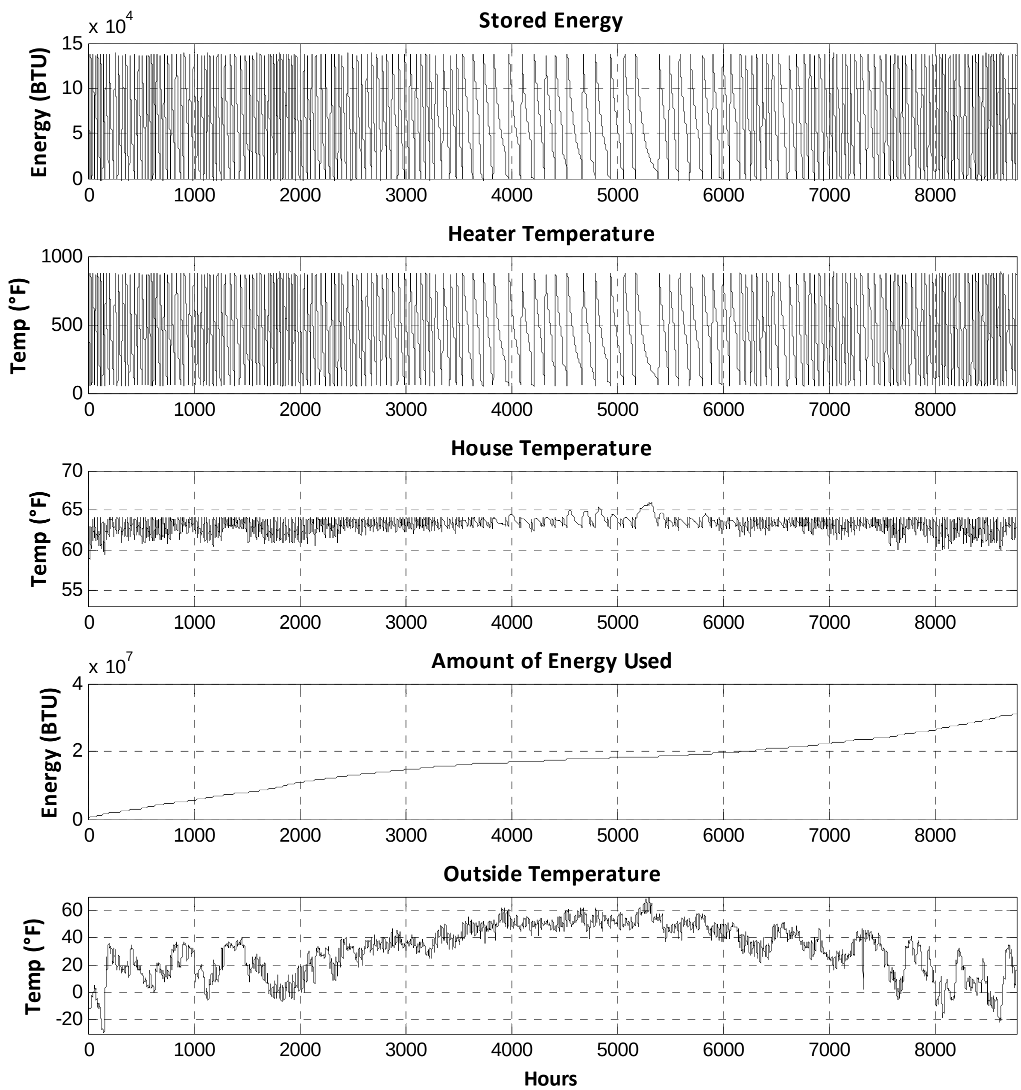

Figure 38: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), Energy Used (BTU), and Outside Temperature (°F) for a Small House in Kongiganak

3.6.7.2 Small House in Unalakleet

The model for a small house in Unalakleet predicted that 33.24 MBTU of energy is required to heat the house, as illustrated in Figure 39. This is close to the value calculated for Kongiganak, but slightly higher due to a slightly lower average yearly temperature.

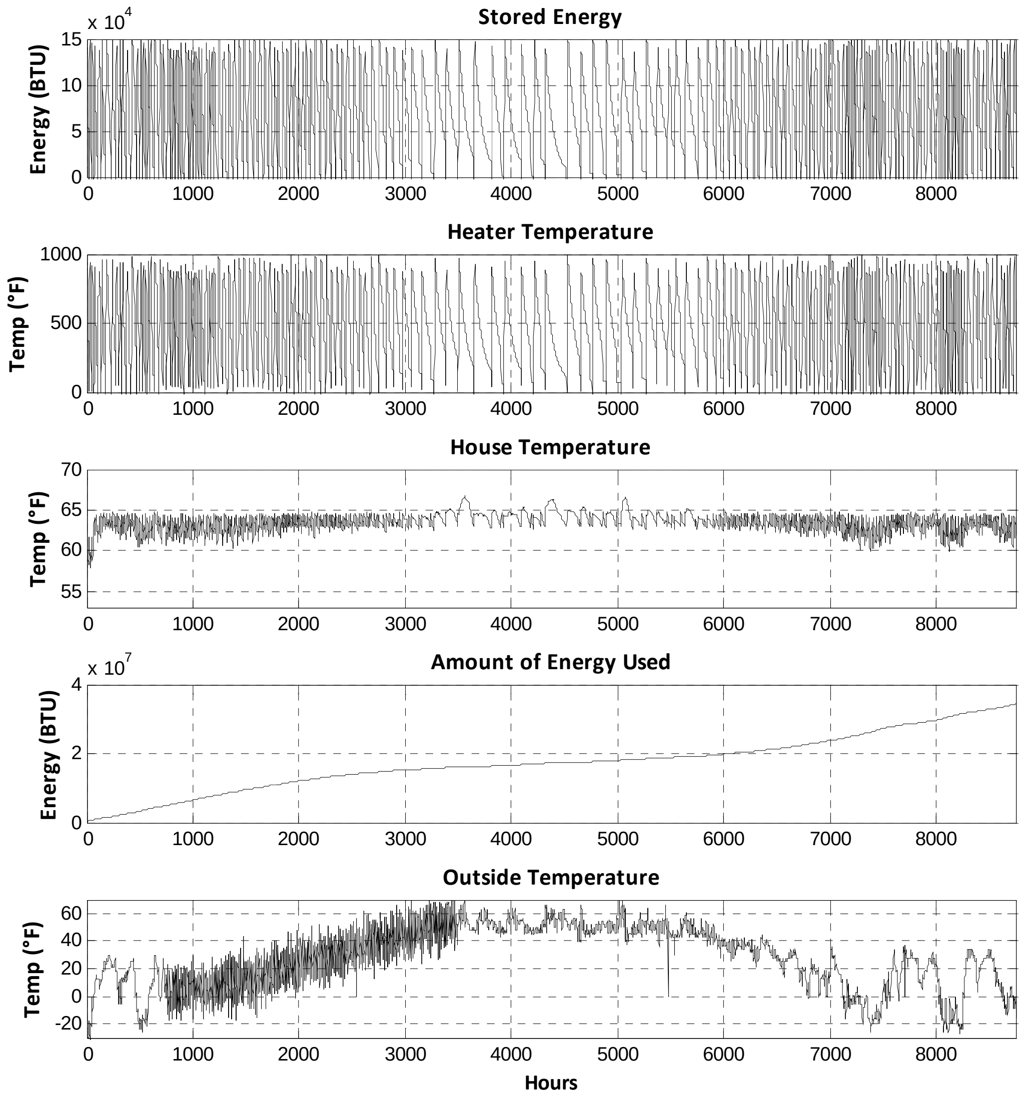

Figure 39: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), Energy Used (BTU), and Outside Temperature (°F) for a Small House in Unalakleet

As shown in Figure 40, in January, Unalakleet's temperature is so cold that the Steffes cannot adequately heat the house for the first few days, but the Steffes charges and meets the heating needs. The stored energy value sometimes dips below 0 BTU because the time step is such that it passes the 0 BTU charge point before charging is activated. Changing step sizes did little to correct this issue, which overall had little effect on the model, as it only dipped <0.1% below 'empty'.

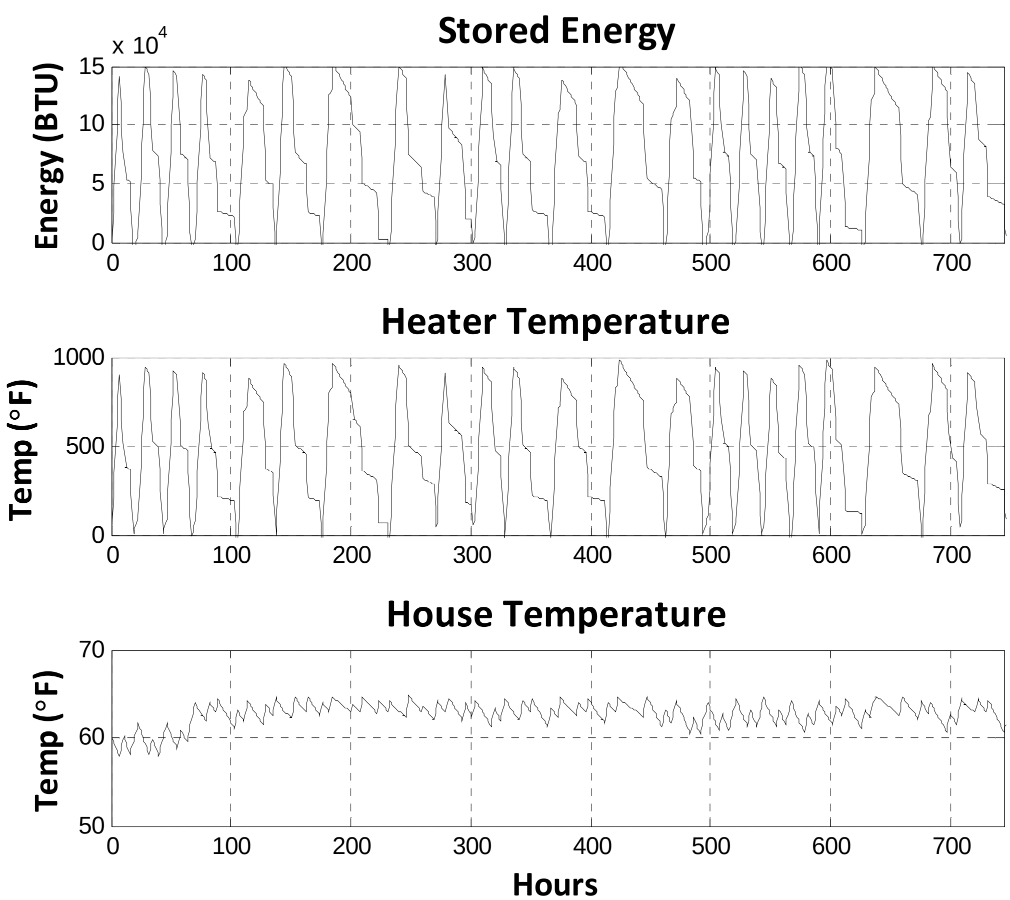

Figure 40: Stored Energy (BTU) in the Steffes, Heater Temperature (°F), and House Temperature (°F) in January in Unalakleet

3.6.8 Bigger House

A bigger house is also modeled with a 20 ft × 30 ft footprint, 20 ft high ceiling, and an insulation value of R-20 in the walls. When the heater is charged with a constant voltage of 240 VAC, and loses energy to a 60 °F house, it takes 5.79 hours to fully charge, with a temperature increase of 807 °F. The house temperature rises from 60 °F to 64.1 °F as illustrated in Figure 41.

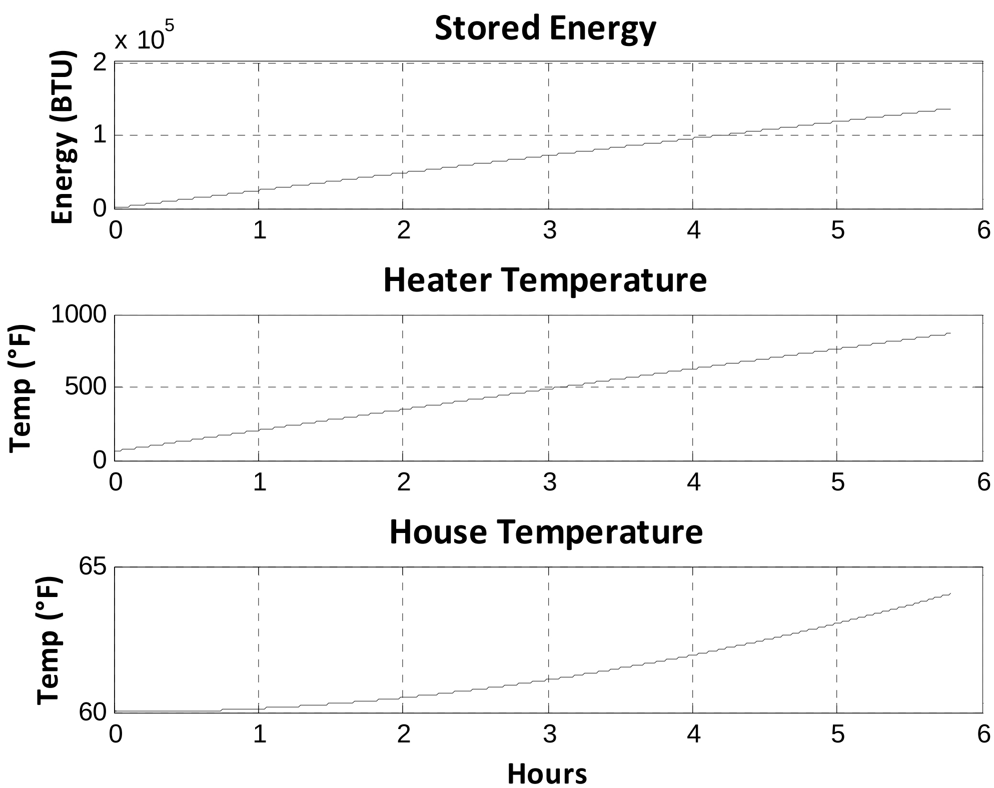

Figure 41: Energy Stored in a Steffes Heater (BTU), Temperature of Steffes Heater (°F), and the Temperature (°F) of the Perfectly Insulated Big House as the Heater Charges

When the fully charged heater (867 °F and 136,480 BTU) discharges to a perfectly insulated 68 °F house, the entire system reaches equilibrium at 500 hours, when the heater and room equilibrate to 153 °F. At this point the heater discharged 134,480 BTU of thermal energy. This is shown in Figure 42.

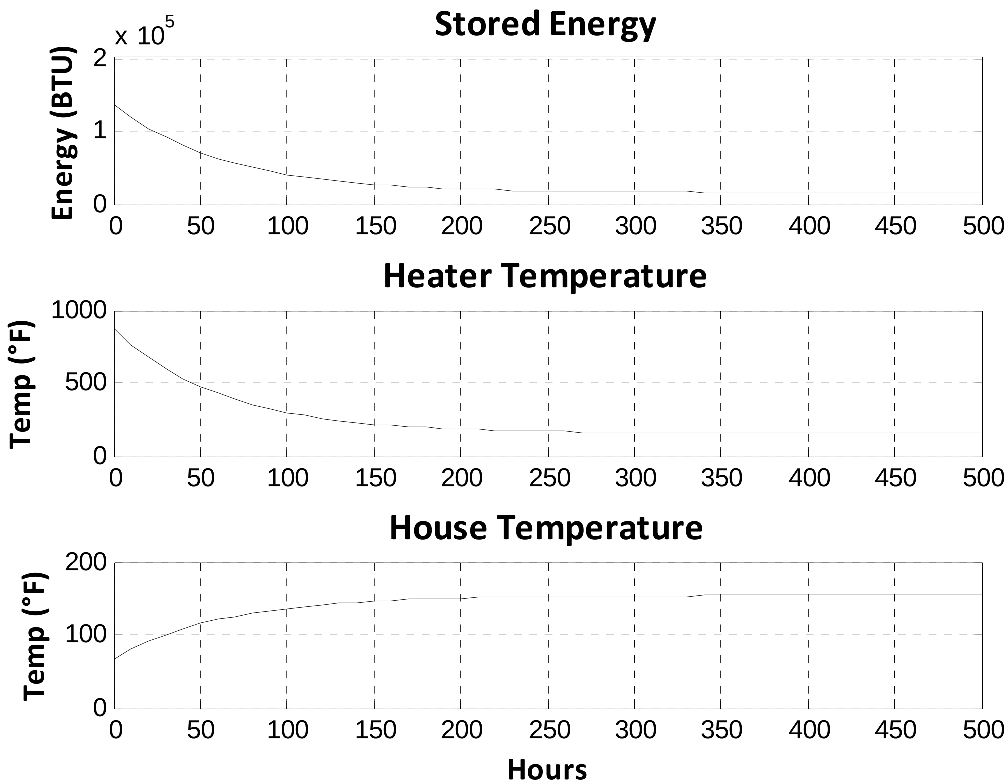

Figure 42: Energy Stored (BTU), Heater Temperature (°F), and House Temperature (°F) for a Fully Charged Steffes Heater Discharging in a Big House

When a 60 °F thermostatically controlled uncharged heater (tolerance of 5 °F) is turned on in a 60 °F room, and the outside temperature is 0 °F, the heater charges in 15 hours. The heater turns on four times, or about once every 3.75 hours, during this period. When the blower is on, the heater gains 5,000 BTU/h; when the blower is off, it gains 25,000 BTU/h. This is shown in Figure 43.

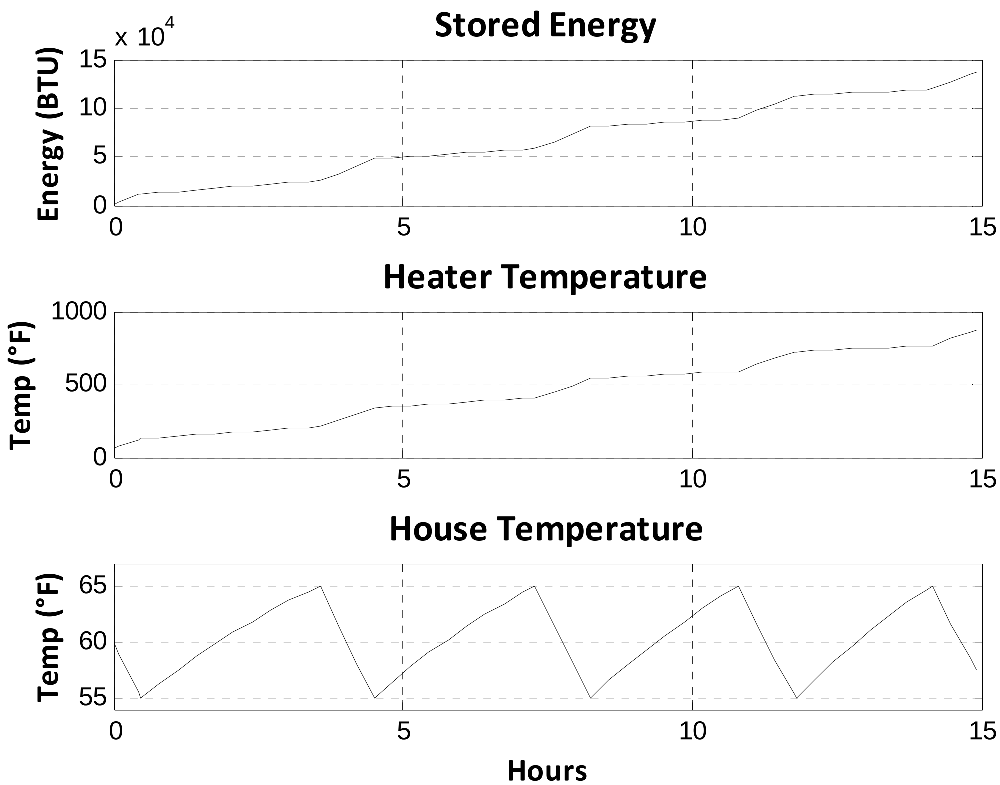

Figure 43: Energy Stored in a Steffes Heater (BTU), Temperature of Steffes Heater (°F), and the Temperature (°F) of the Big House as the Heater Charges and the Thermostat Regulates the House Temperature

A fully-charged thermostatically-controlled heater discharges to a 60 °F lossy house, with an outside temperature of 0 °F in 8.7 hours. The thermostat turns on three times, once every 3 hours, each time for approximately 1.5 hours, as shown in Figure 44.

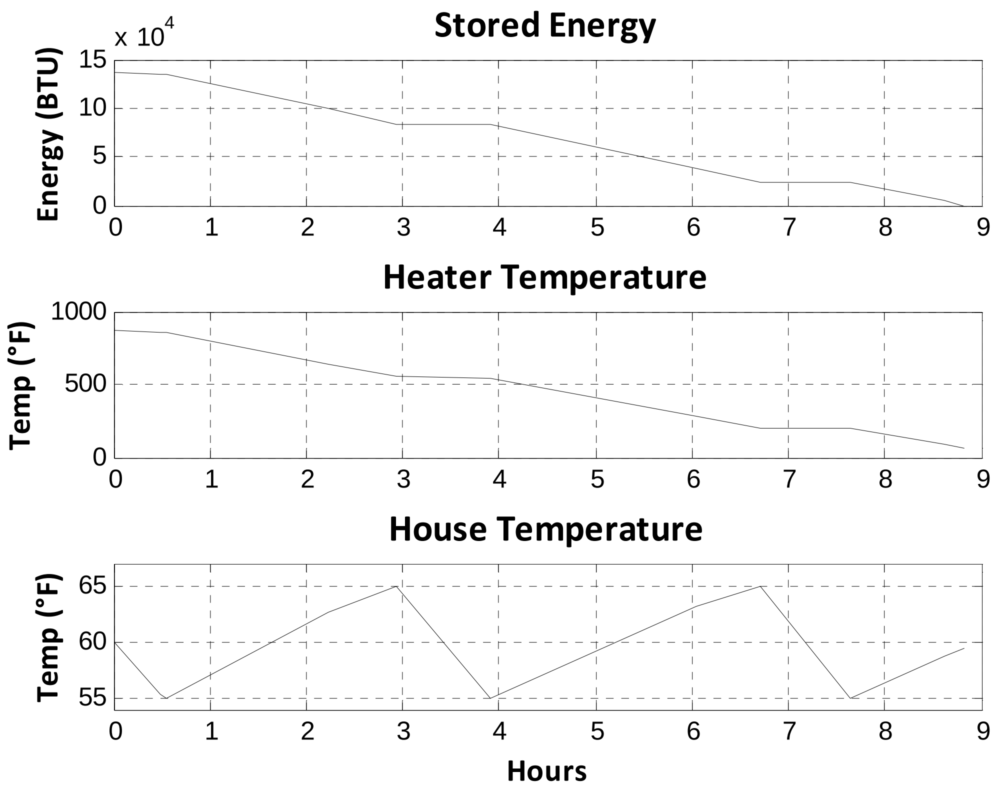

Figure 44: Energy Stored (BTU), Heater Temperature (°F), and House Temperature (°F) for a Fully-Charged, Thermostatically-Controlled Steffes Heater Discharging in a Big House

These results are summarized in Table 6.

Table 6: Time to Charge and Discharge Big House under Various Conditions (Hours)

Charging/ Discharging	Condition	Thermostat?	Time to Charge/ Discharge (hrs)
Charge	House	No	5.79
Discharge	House	No	N/A (>500)
Charge	Lossy House	No	15
Discharge	Lossy House	No	N/A (>200)
Charge	Very Lossy House	Yes	14.9
Discharge	Very Lossy House	Yes	8.7

3.6.8.1 Bigger House in Kongiganak

Heating a bigger house in Kongiganak requires 65.08 MBTU of heat over the course of the year, as shown in Figure 45. Over the course of the year, more energy is used during the colder winter months, and so the heater charges and discharges more often than it does during the summer months.

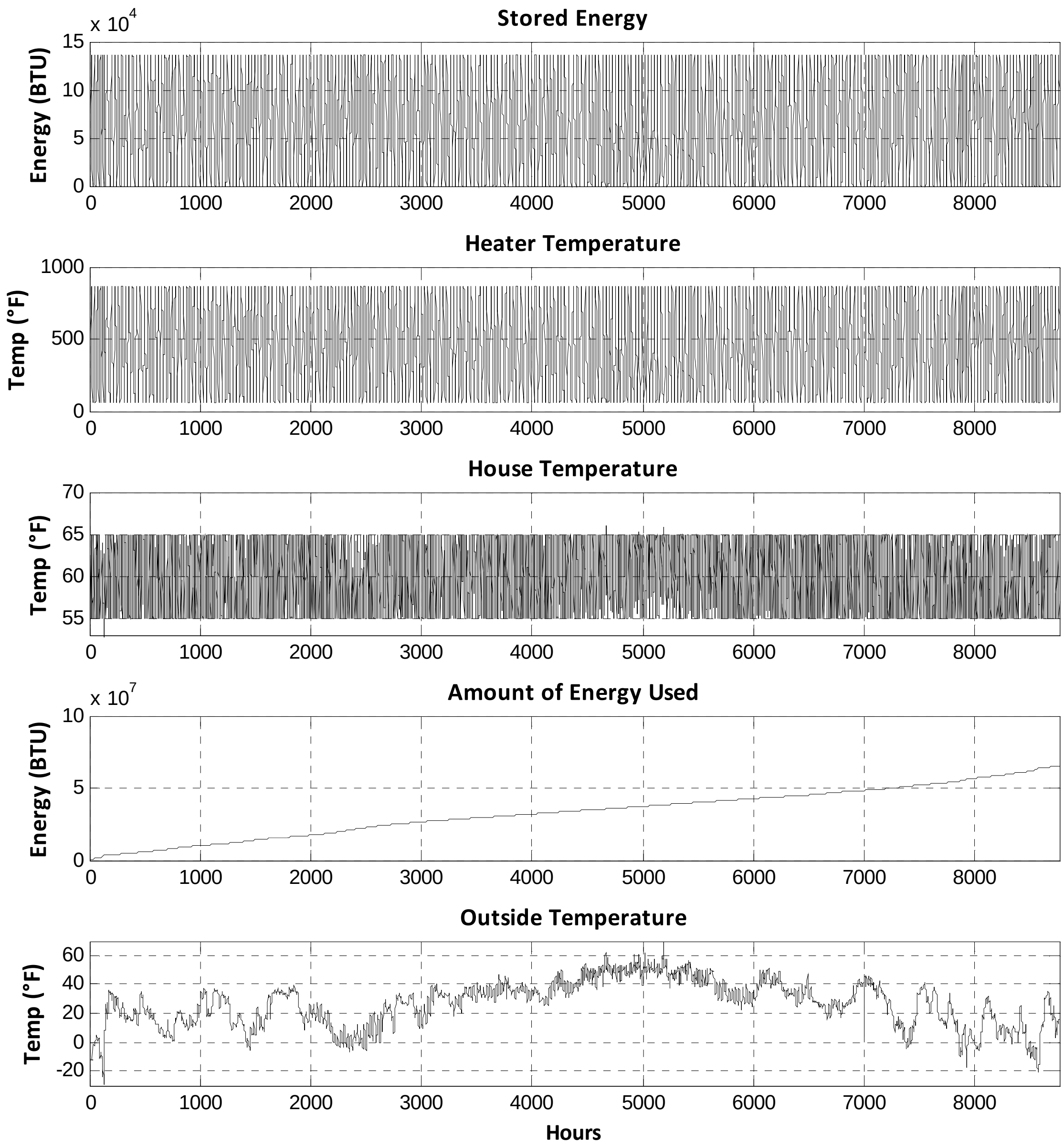

Figure 45: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), Energy Used (BTU), for a Bigger House in Kongiganak, and Kongiganak's Outside Temperature (°F)

Month-long slices of stored energy, heater temperature (°F) and house temperature (°F) are shown in Figure 46 through Figure 48 for January, May, and October, respectively. In January, the heater charges and discharges more often than it does in October, which charges more often than it does in May when the weather is warmer and less energy is demanded.

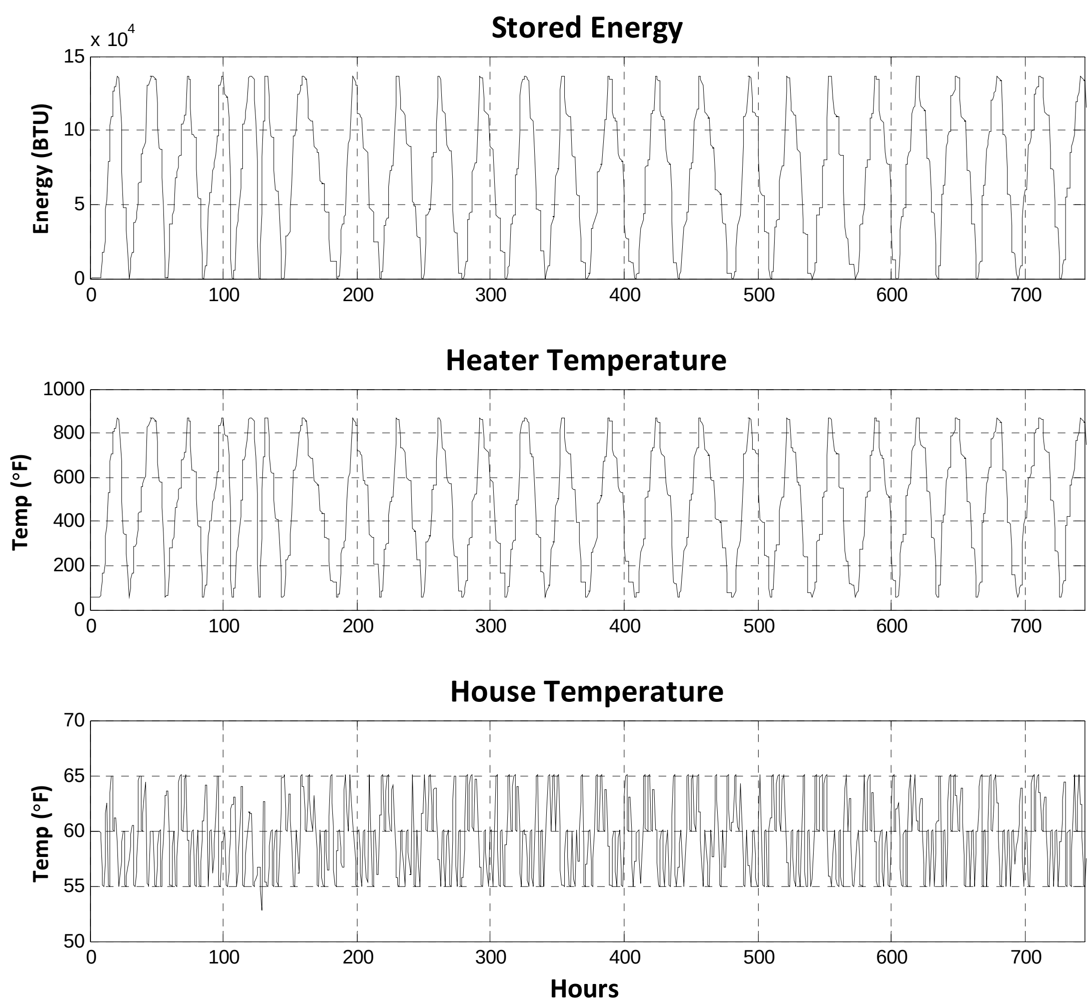

Figure 46: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F) for a Bigger House in Kongiganak in January

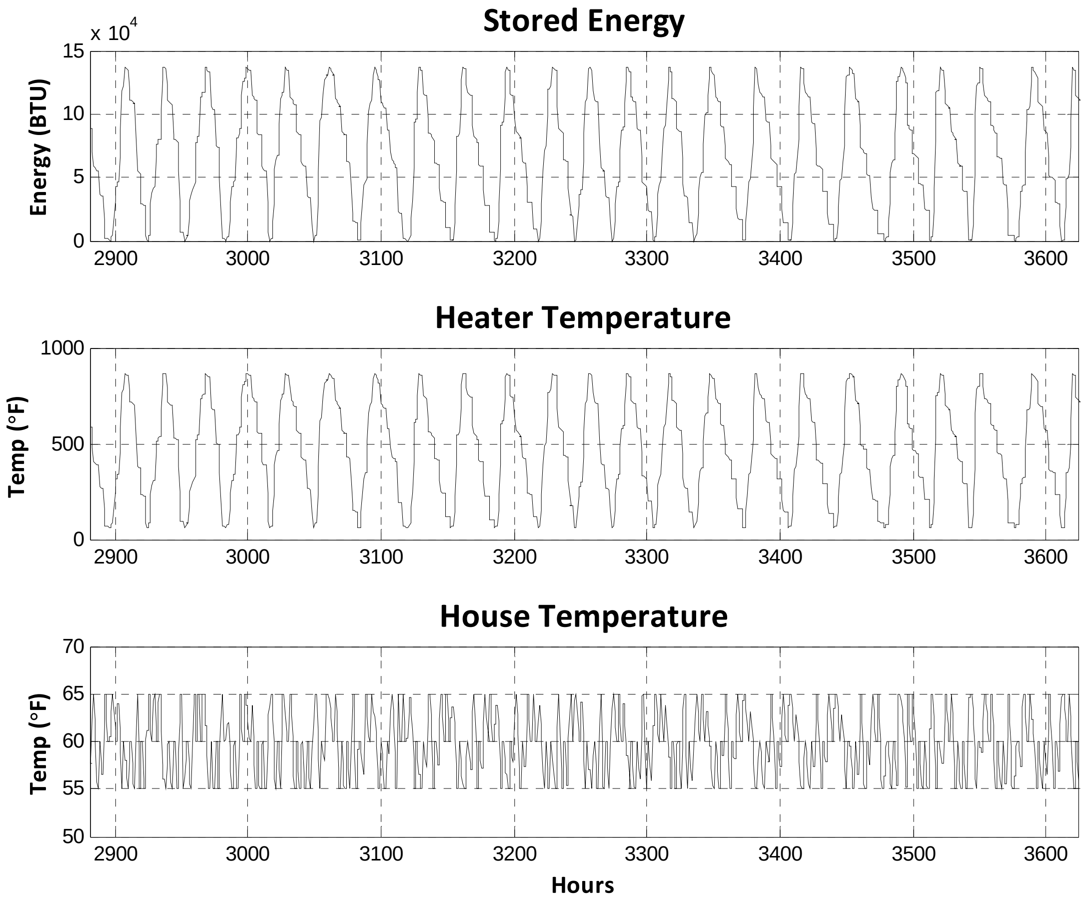

Figure 47: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F) for a Bigger House in Kongiganak in May

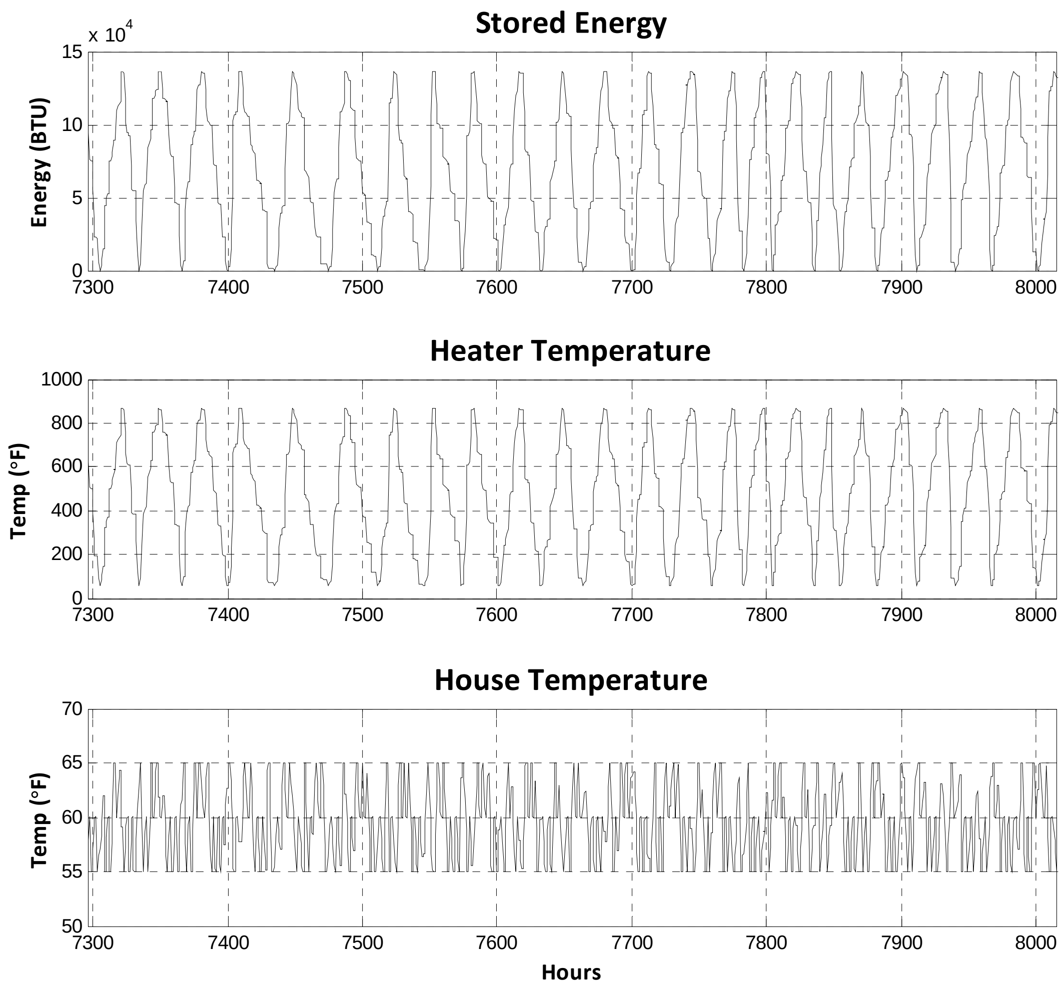

Figure 48: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F) for a Bigger House in Kongiganak in October

3.6.8.2 Bigger House in Unalakleet

Heating a big house in Unalakleet requires 72.82 MBTU of heat over the course of the year, as shown in Figure 49. Since Unalakleet's average temperature is lower than Kongiganak's, more energy is required. Because its summer is milder and longer, there is a longer period of time when not a lot of heating energy is used.

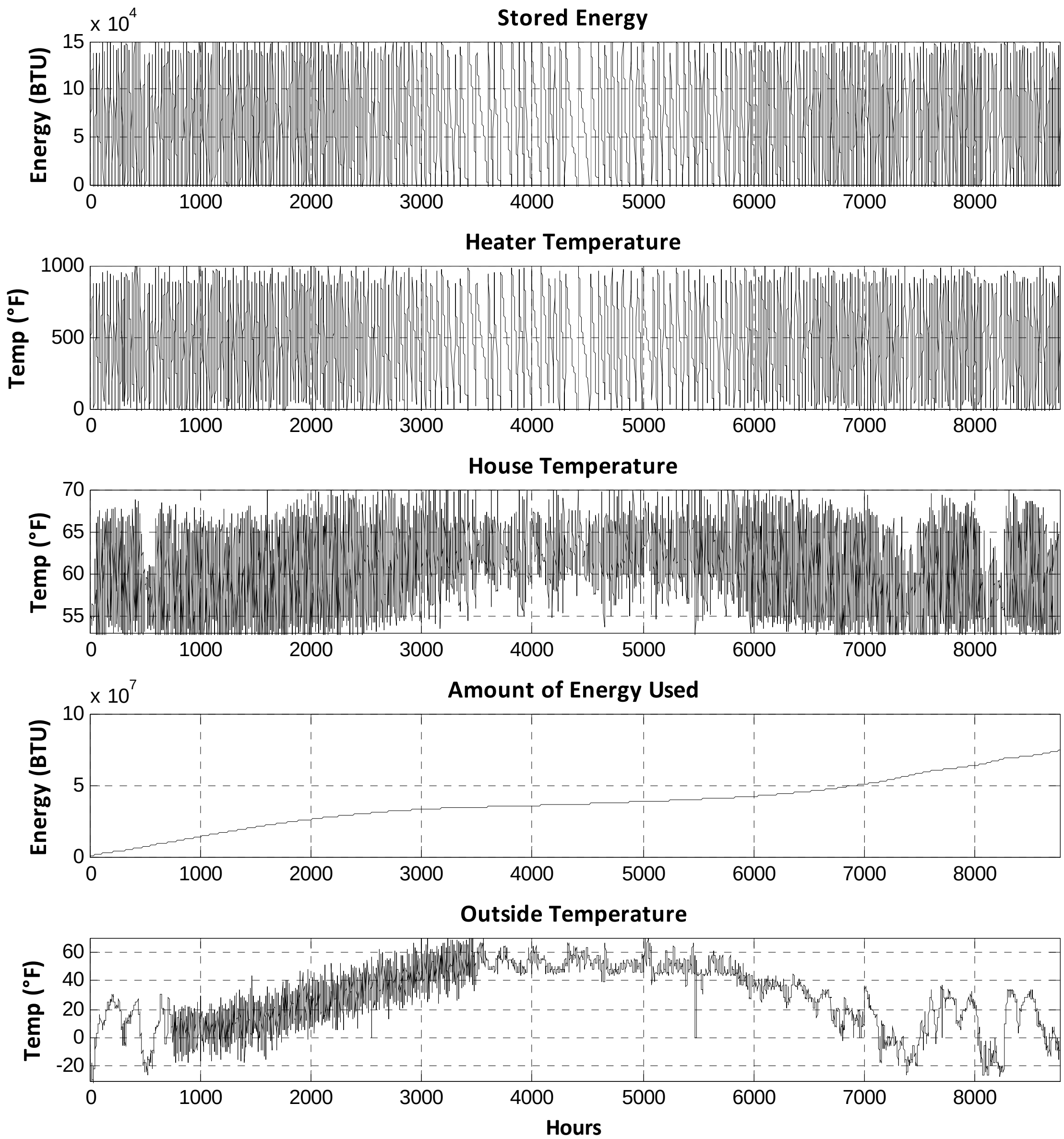

Figure 49: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), Energy Used (BTU), for a Bigger House in Unalakleet, and Unalakleet's Outside Temperature (°F)

Figure 50 through Figure 52 show stored energy, heater temperature, and house temperature for a bigger house in Unalakleet for January, May, and October. In January, the first few hours take a while to 'warm up', which is probably due to -20 °F outside temperatures in the first few days in the beginning of the year, before the heater is charged. Once the heater warms up, it meets the heating needs more effectively.

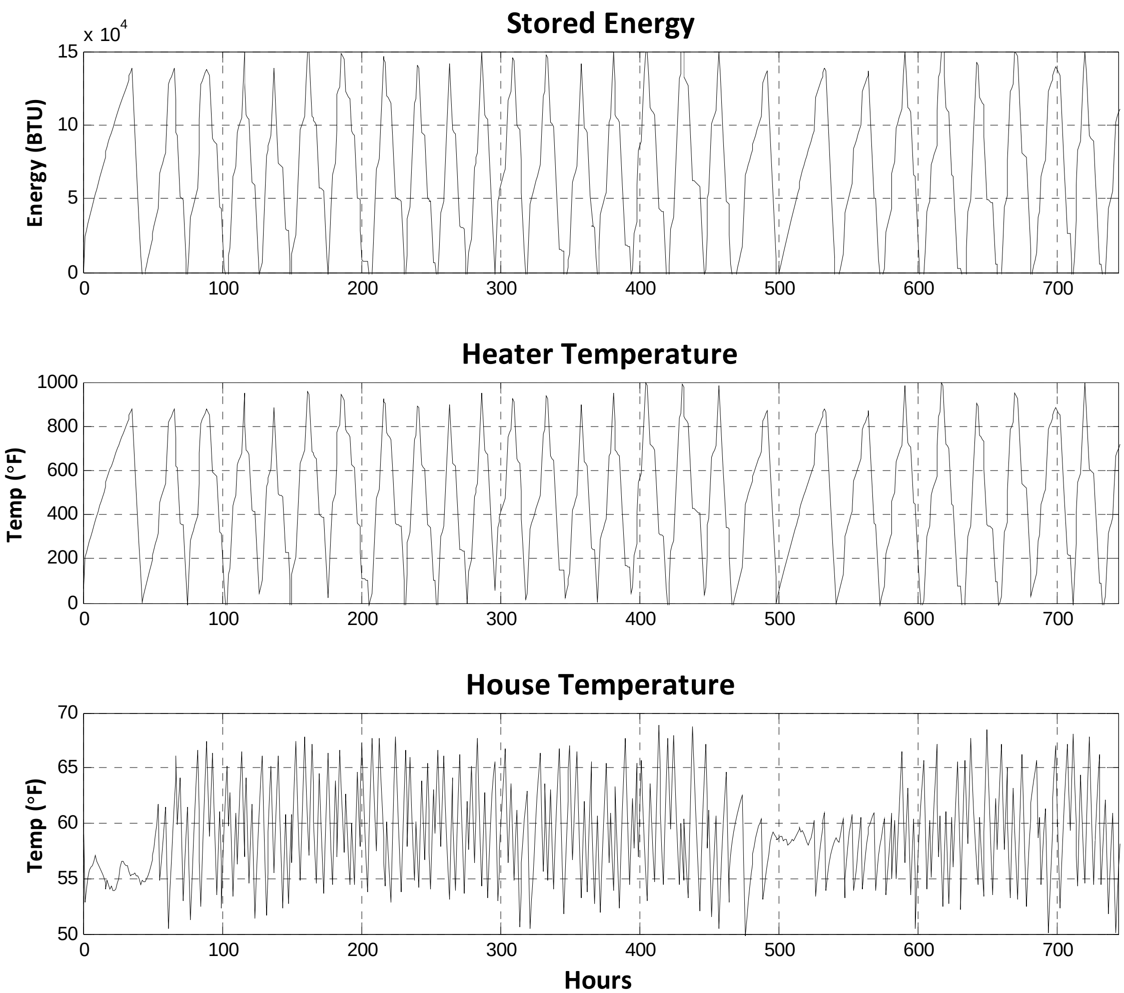

Figure 50: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Bigger House in Unalakleet in January

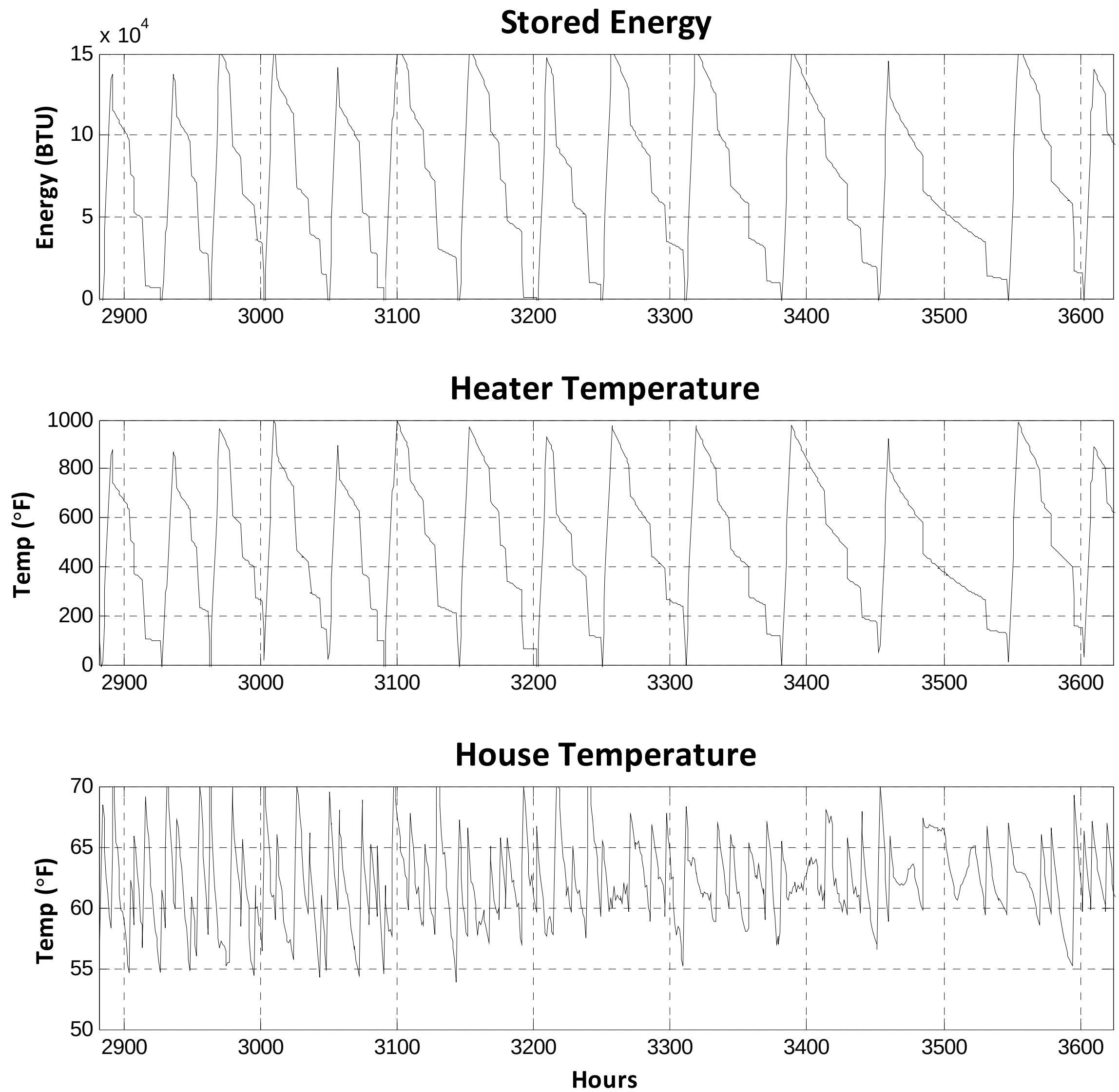

Figure 51: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Bigger House in Unalakleet in May

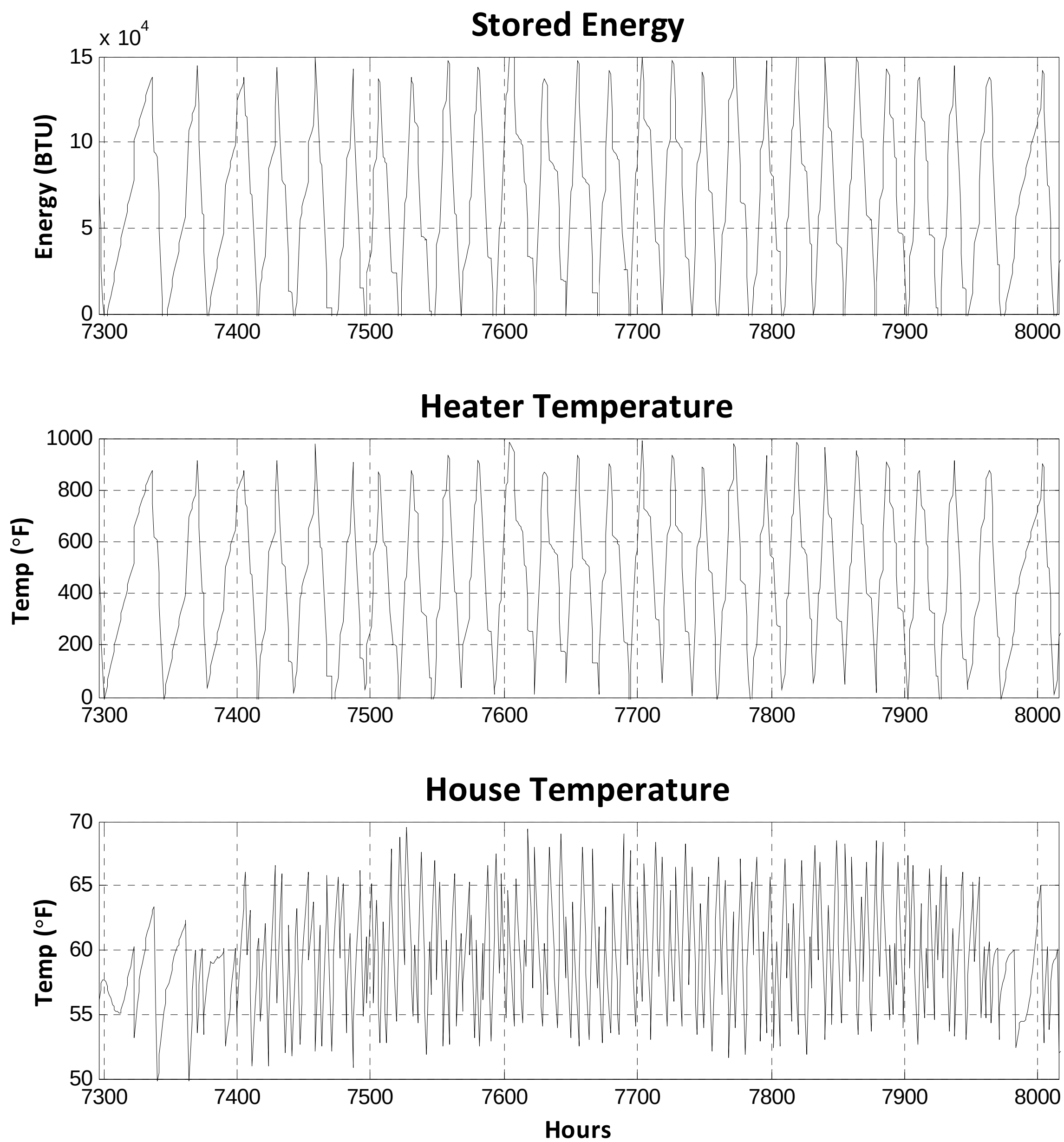

Figure 52: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Bigger House in Unalakleet in October

3.6.9 Community Center

A community center is modeled as a building with a 45 ft × 30 ft footprint, a 20 ft ceiling, and an insulation value of R-20 in the walls. Calculations revealed that heating a community center with these dimensions, a 0°F outside temperature, and an insulation value R-20 requires 130.2 MBTU of heat. The Kongiganak community center was heated with 123.52 MBTU, slightly less as Kongiganak's average temperature is warmer, as shown in Figure 53.

A heater charged with a constant voltage of 240 VAC, which loses heat to a 60 °F building, requires 5.79 hours to fully charge with the same temperature increase. The house temperature rises from 60 °F to 61.6 °F.

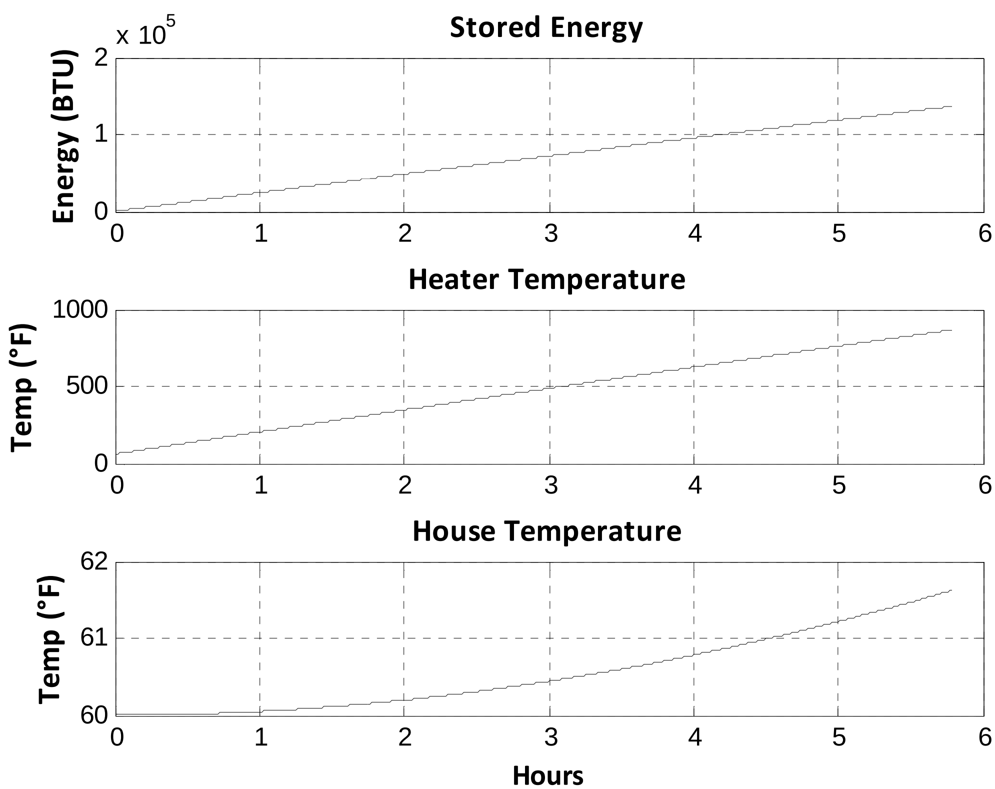

Figure 53: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Charging Heater in a 60°F Insulated Community Center

When the fully charged heater (867 °F and 136,480 BTU) discharges in a perfectly insulated 60.9 °F house, the entire system reaches equilibrium at 732 hours (30.5 days) when the heater and room equilibrate to 104.7 °F, and the heater stores 3650 BTU. For practicality, Figure 54 shows the first 400 hours, when the temperatures start to approach equilibrium.

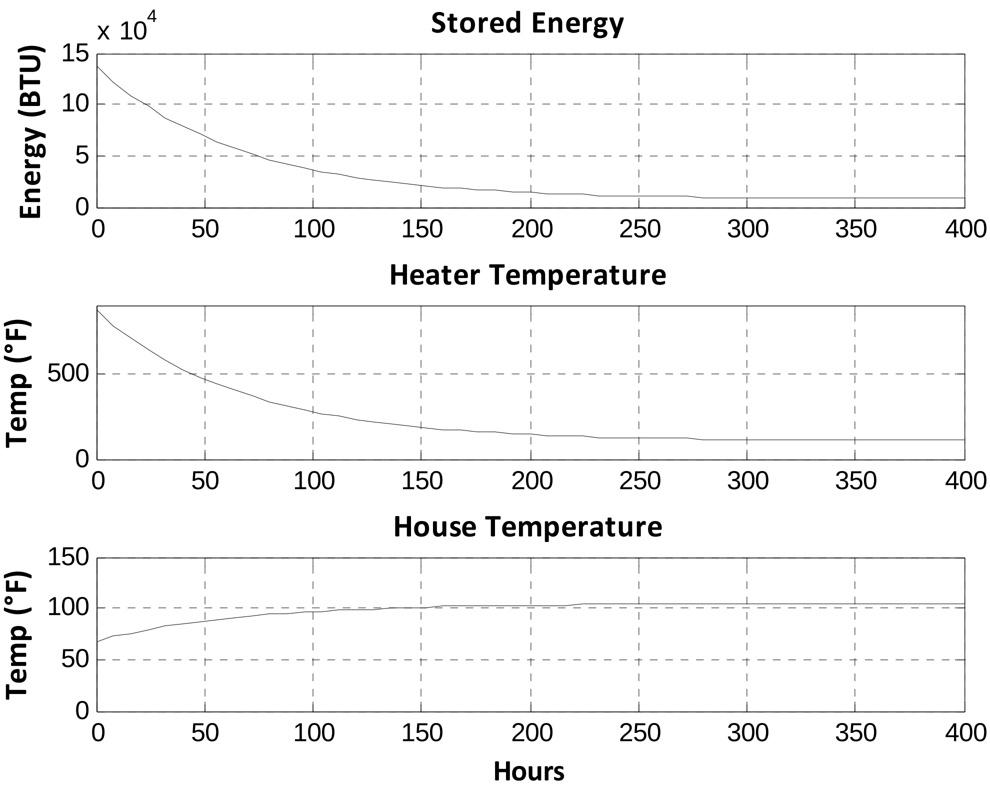

Figure 54: Energy Stored in the Heater (BTU), Temperature of the Heater (°F), Temperature of the House (°F), for a Charged Heater Discharging in a Community Center

A thermostatically-controlled uncharged, 60 °F heater is turned on in a 60 °F lossy room with a 0 °F outside. It takes 37 hours to charge, and the house loses heat to the outside so quickly that it becomes too cold to inhabit. When the thermostat turns the blower on, the heater transfers 22,000 BTU/h, to the room. The losses of the building to the outside air are greater (25,000-30,000 BTU/h) than the heat transfer rate from the heater as shown in Figure 55. One heater is insufficient to meet the community center's heating needs. The community center requires two Steffes units to meet its heating needs.

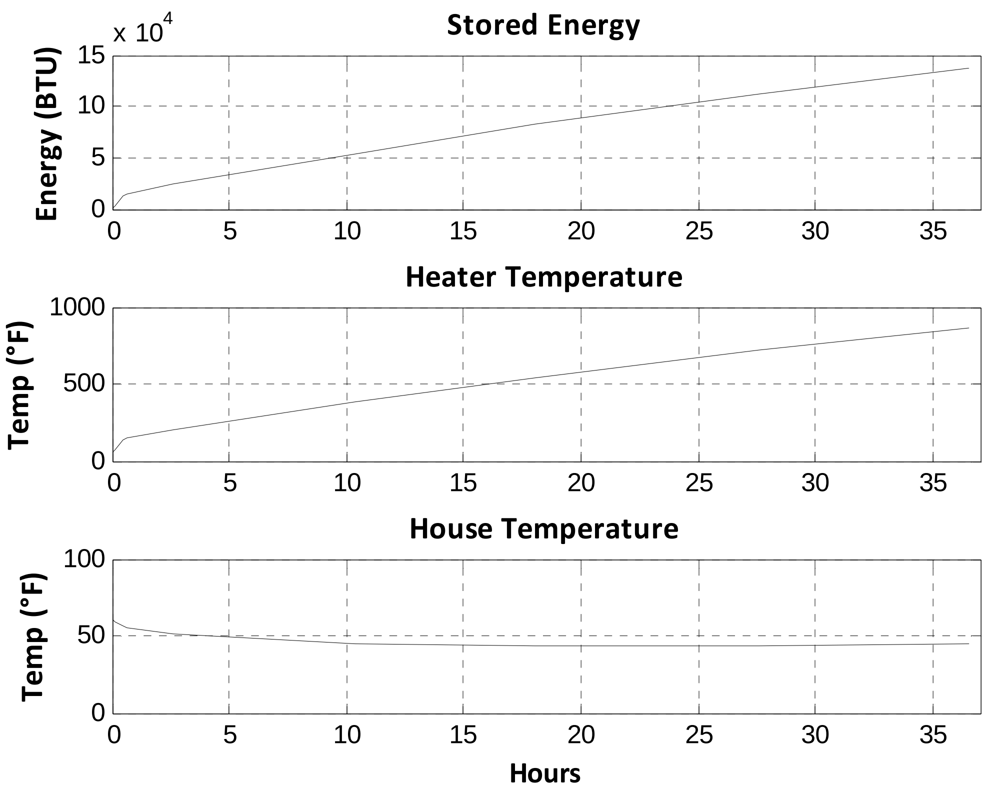

Figure 55: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), for a Charged Heater Discharging in a Community Center

Two 60 °F uncharged heaters are turned on in a 60 °F thermostatically-controlled, perfectly insulated room. The thermostat's tolerance is 1 °F. The heaters charge in 16.2 hours, turning on twice during this period. When the blower is on, the heater experiences a net gain of 5,000 BTU/h; when the blower is off, it gains 25,000 BTU/h as shown in Figure 56.

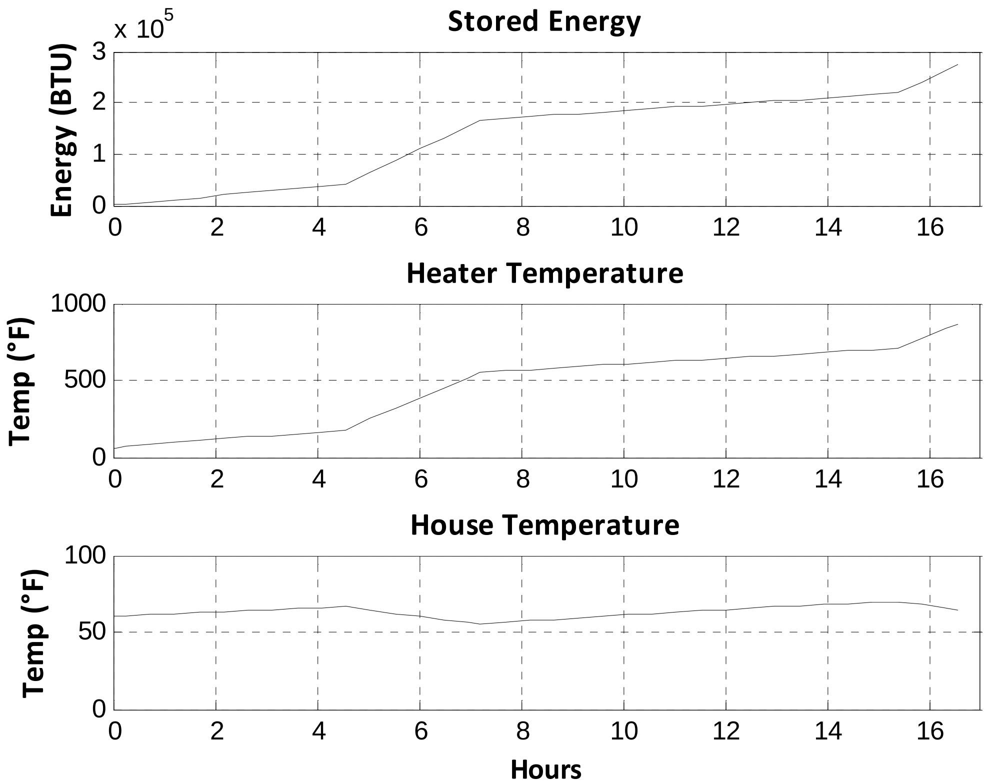

Figure 56: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), for Two Thermostatically-Controlled Heaters Charging in a Lossy Community Center

When two fully charged, thermostatically-controlled heaters discharge in a 61.9 °F lossy room and a 0 °F outside environment, the heater reaches a full discharge in 9.2 hours. The thermostat turns the blower on twice, as shown in Figure 57.

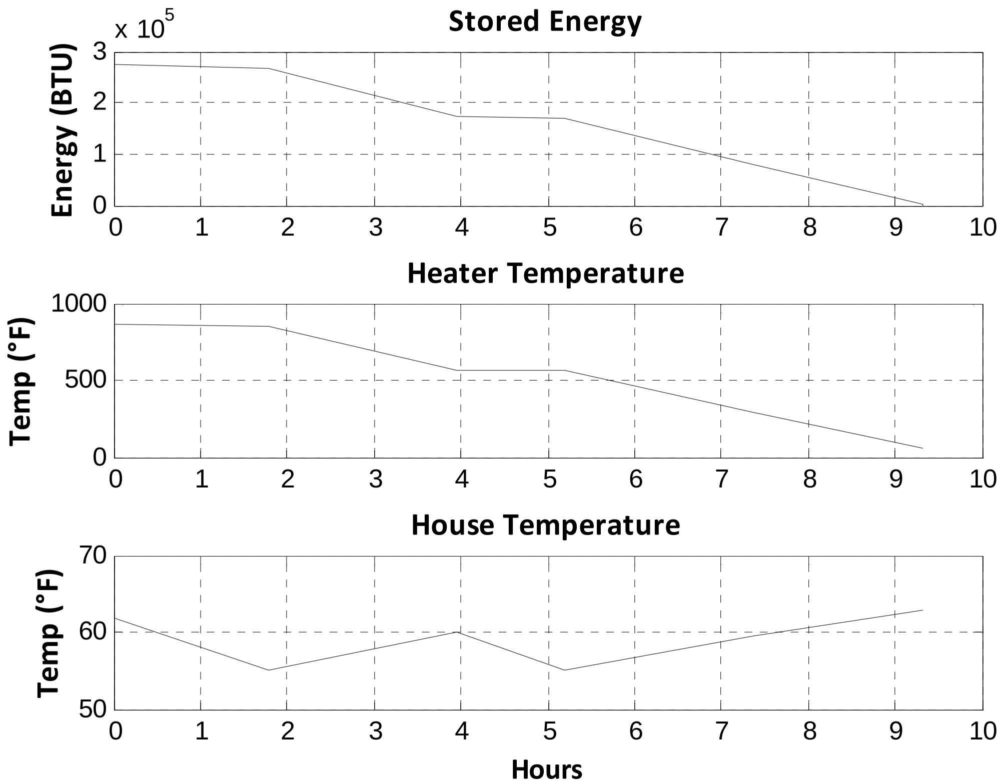

Figure 57: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), for Two Thermostatically-Controlled Heaters Discharging in a Lossy Community Center

These results are summarized in Table 7.

Table 7: Time to Charge and Discharge Community Center under Various Conditions (Hours)

Charging/ Discharging	Condition	Thermostat?	Time to Charge/ Discharge (hrs)
Charge	House	No	5.79
Discharge	House	No	NA (>732)
Charge	Lossy House	No	37
Discharge	Lossy House	No	NA (>480)
Charge	Lossy House	Yes	16.2
Discharge	Lossy House	Yes	9.2

3.6.9.1 Community Center in Kongiganak

Heating the community center in Kongiganak requires 124 MBTU of heat over the course of the year, as shown in Figure 58. This corresponds well relative to the other buildings, as it takes nearly twice as much energy to charge as it did to charge the big house, which is half as big (in terms of interior volume, which determines the amount of energy that can be stored in the air inside the structure).

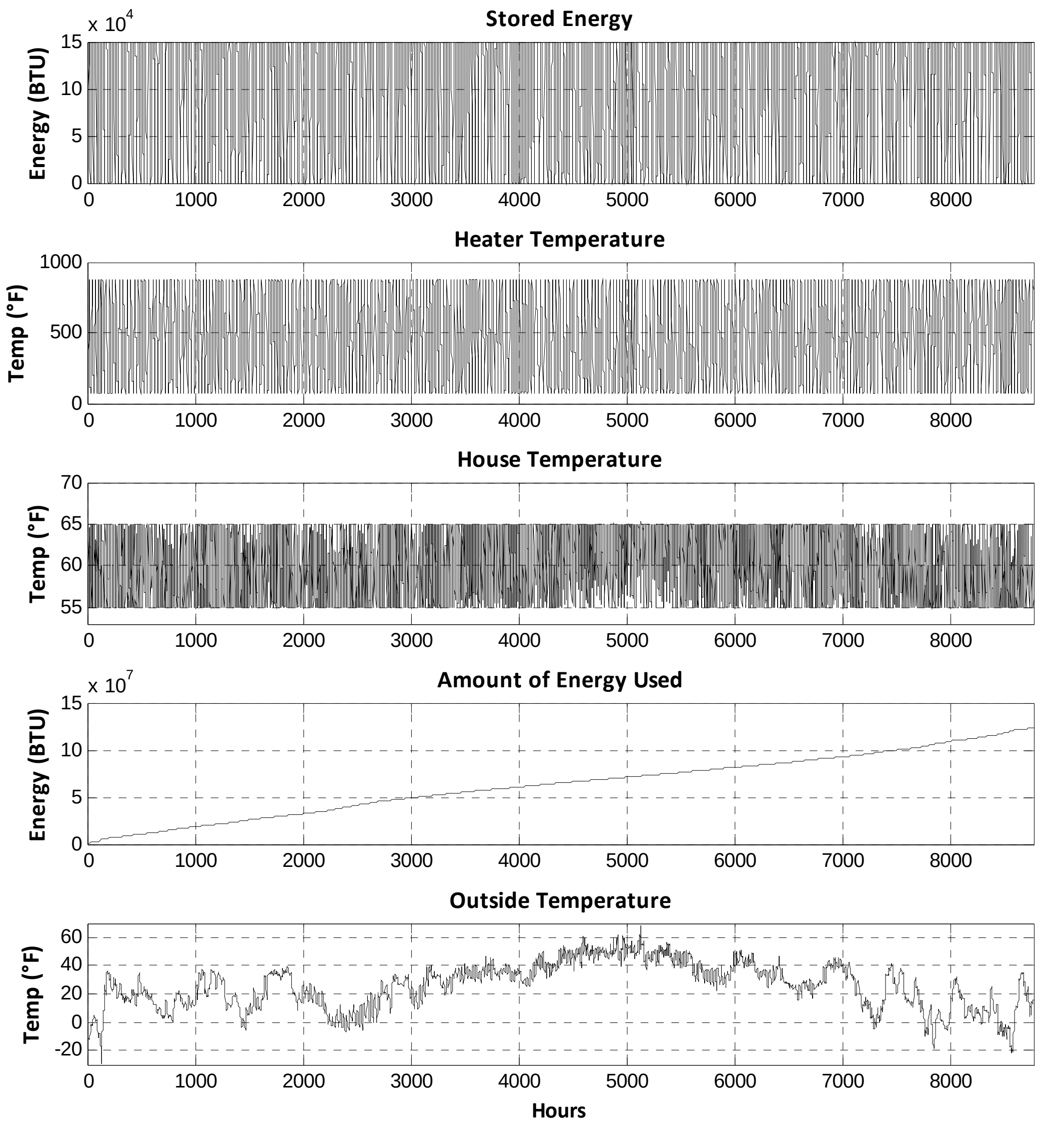

Figure 58: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), Energy Used (BTU), and Outside Temperature (°F) for a Community Center in Kongiganak

Figure 59 through Figure 61 show stored energy, heater temperature, and house temperature for a community center in Kongiganak for January, May, and October, respectively. Like the previous monthly models, the heater discharges more during January than October, and more during October than May.

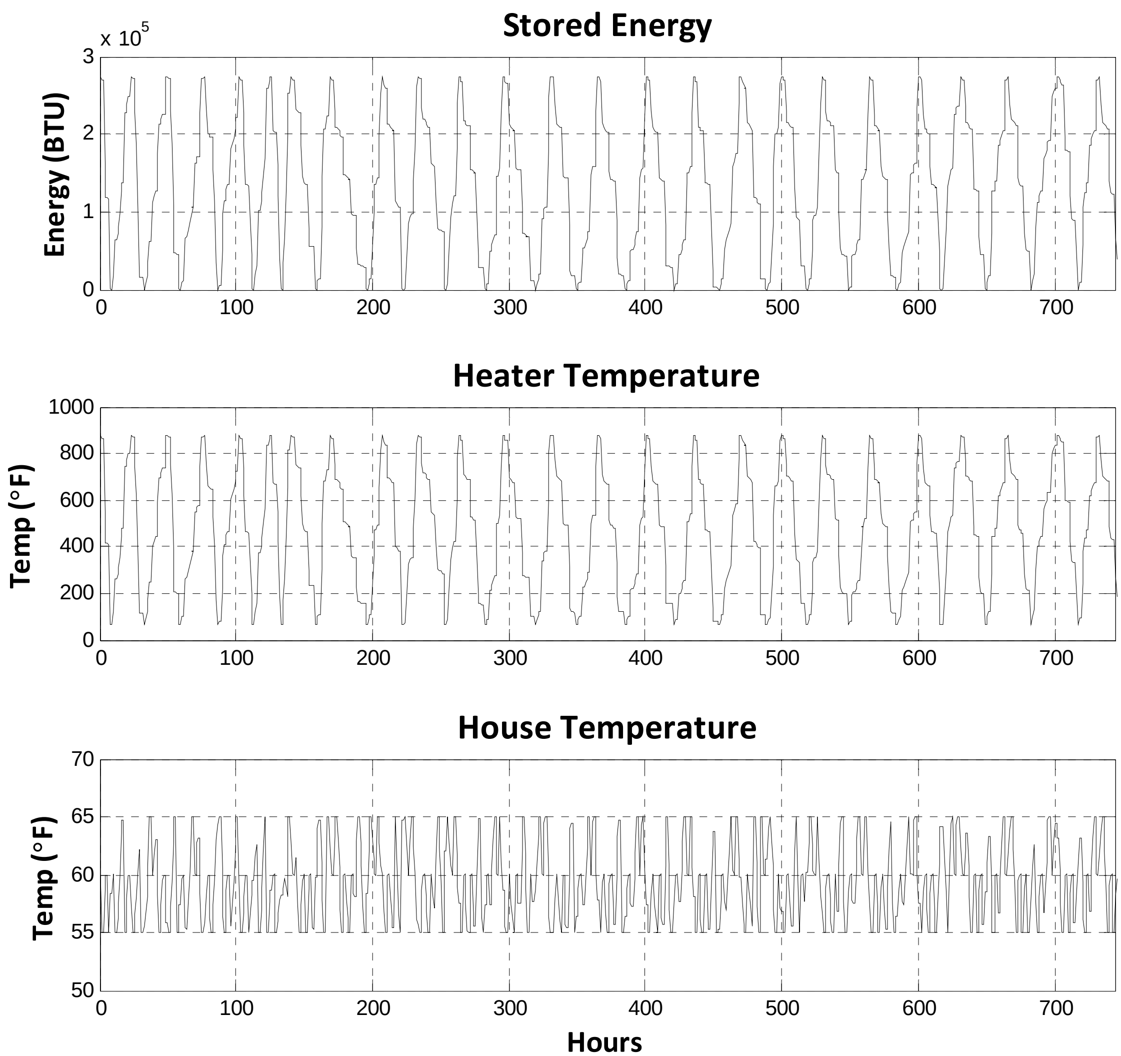

Figure 59: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Community Center in Kongiganak in January

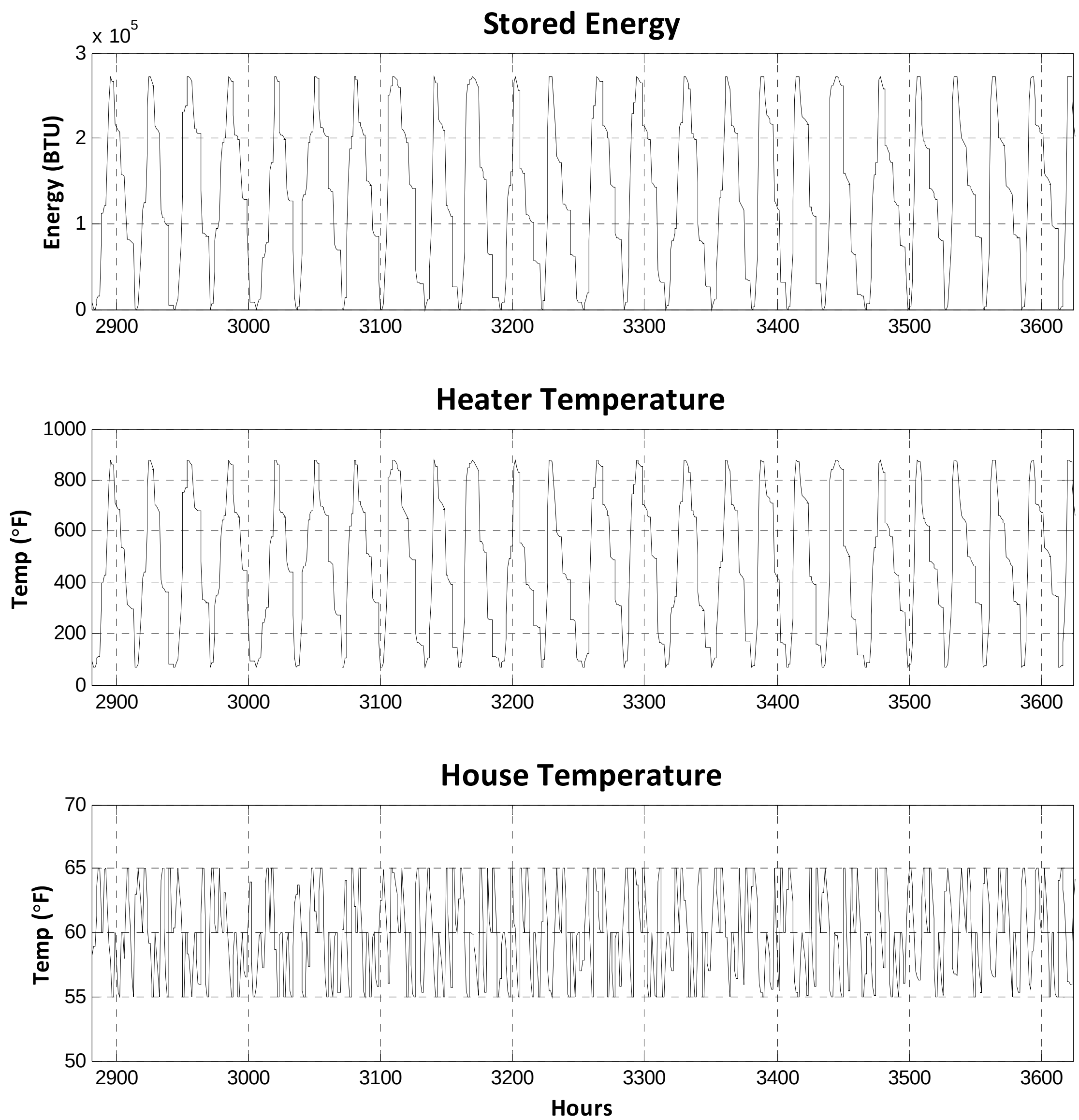

Figure 60: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Community Center in Kongiganak in May

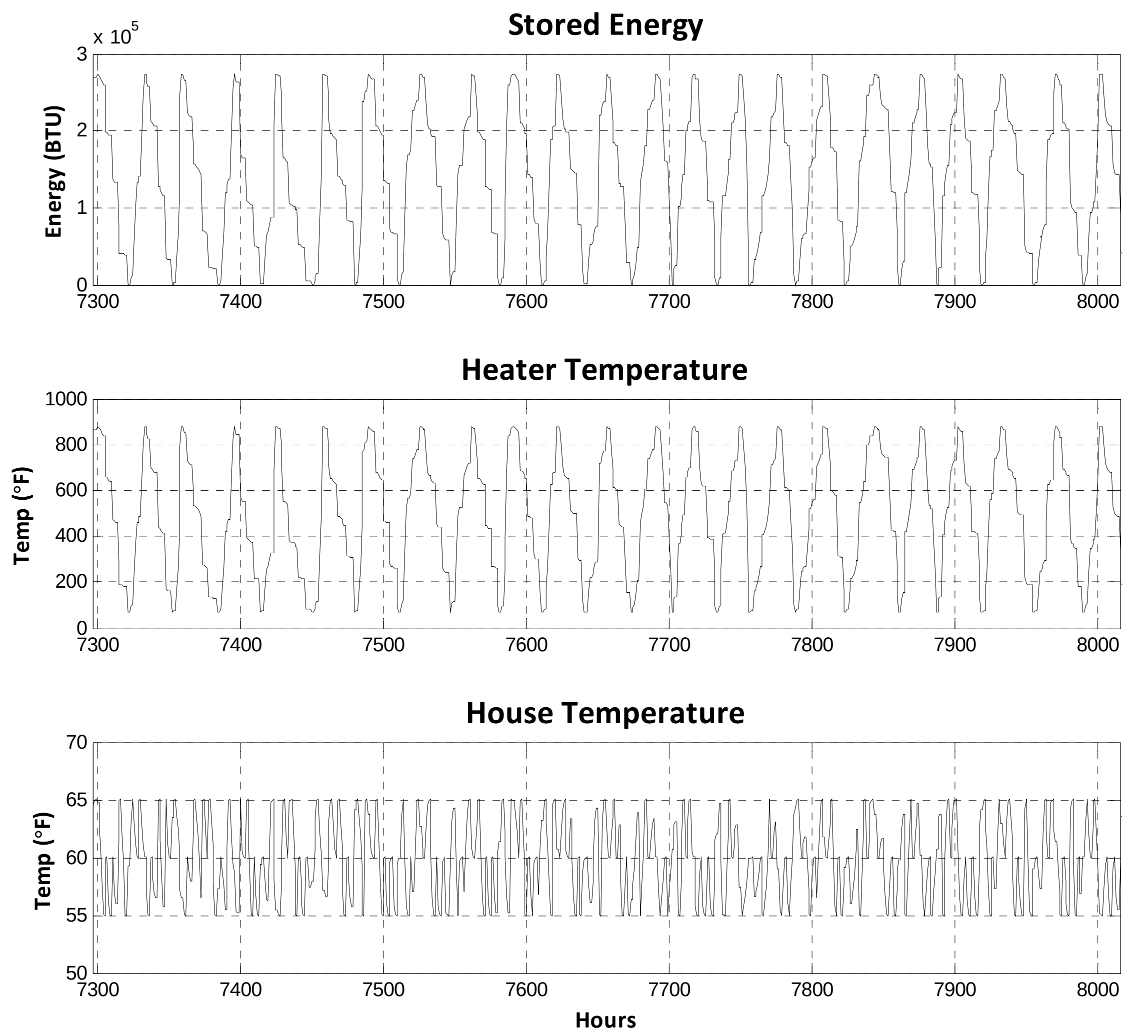

Figure 61: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Community Center in Kongiganak in October

3.6.9.2 Community Center in Unalakleet

Heating a community center in Unalakleet requires 138 MBTU of heat over the course of the year, as shown in Figure 62. This is nearly twice as much as it takes to heat the big house.

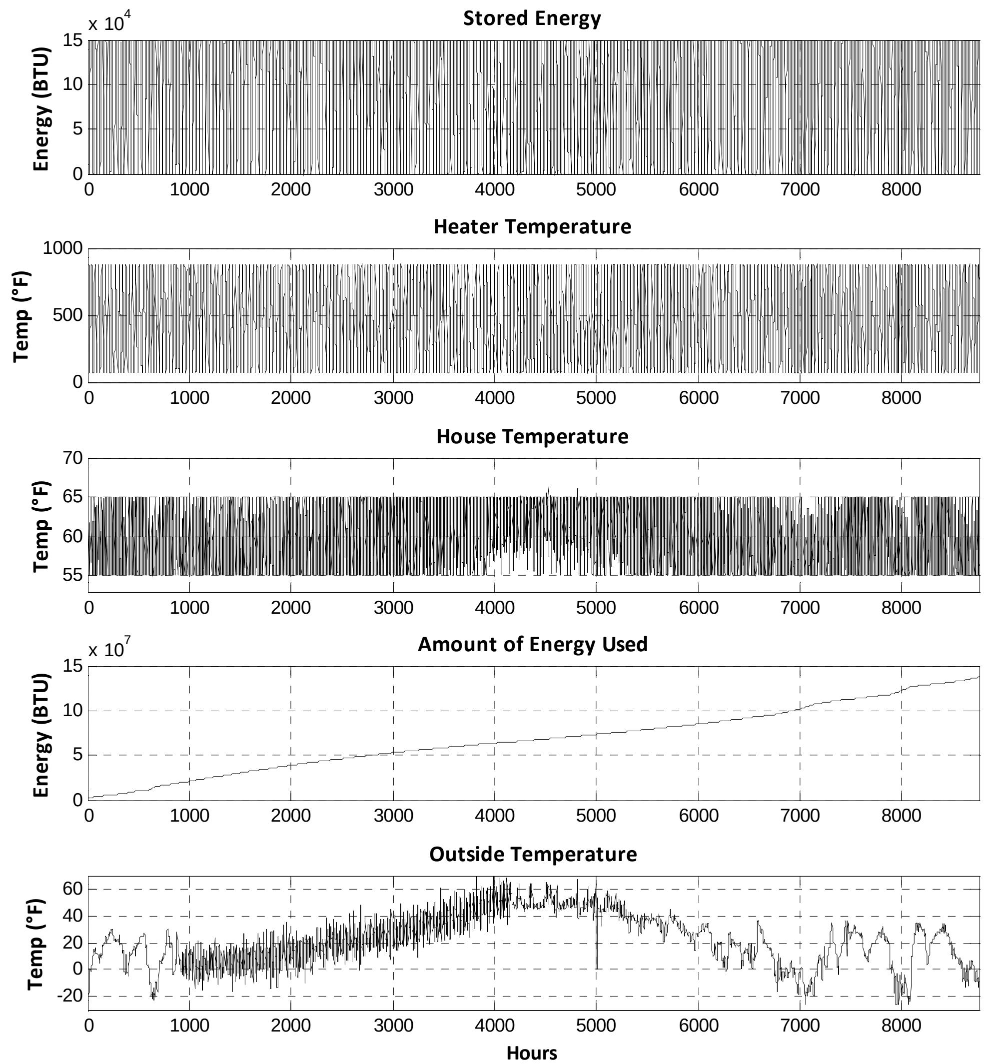

Figure 62: Energy Stored in Heater (BTU), Temperature of Heater (°F), Temperature of House (°F), and Energy Used (BTU) for a Community Center in Unalakleet

Figure 63 through Figure 65 through show stored energy, heater temperature, and house temperature for a community center in Unalakleet for January, May, and October, respectively. The heater discharges more during January than October, and more during October than May.

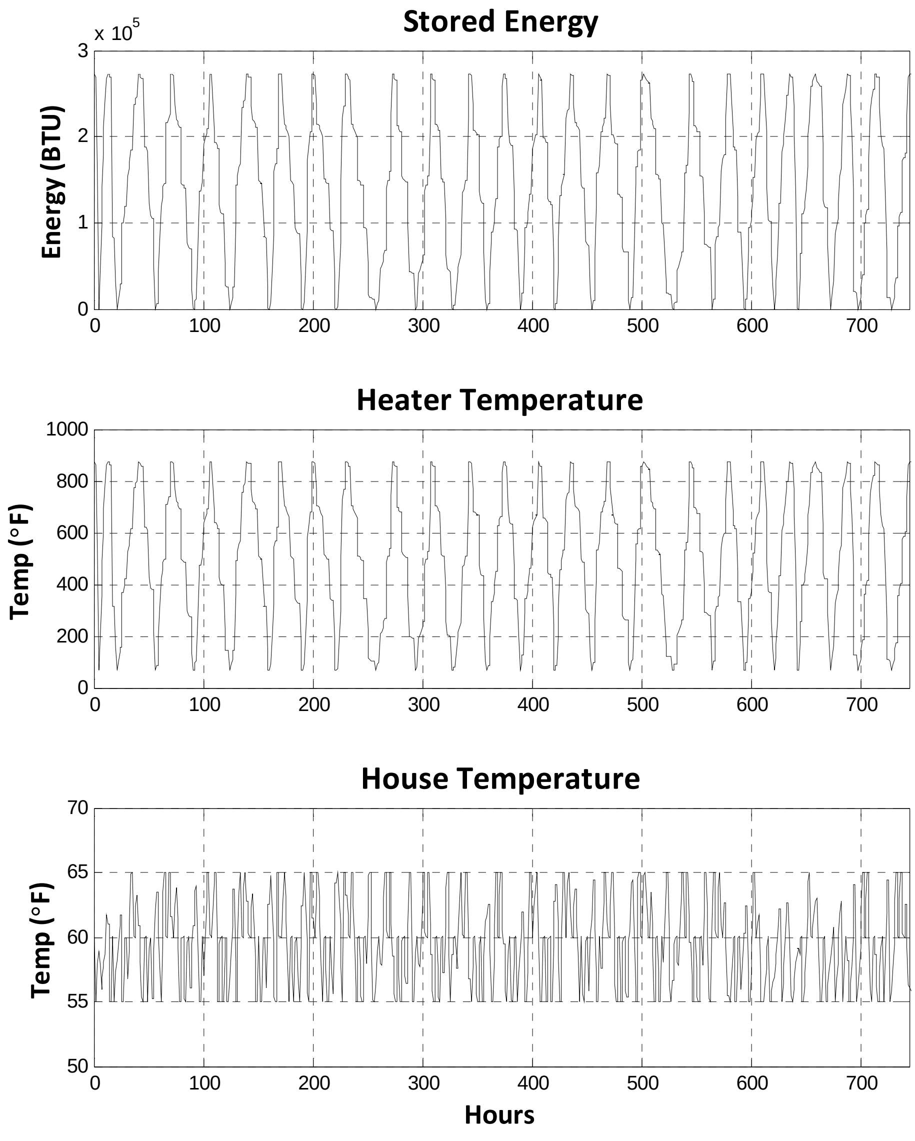

Figure 63: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Community Center in Unalakleet in January

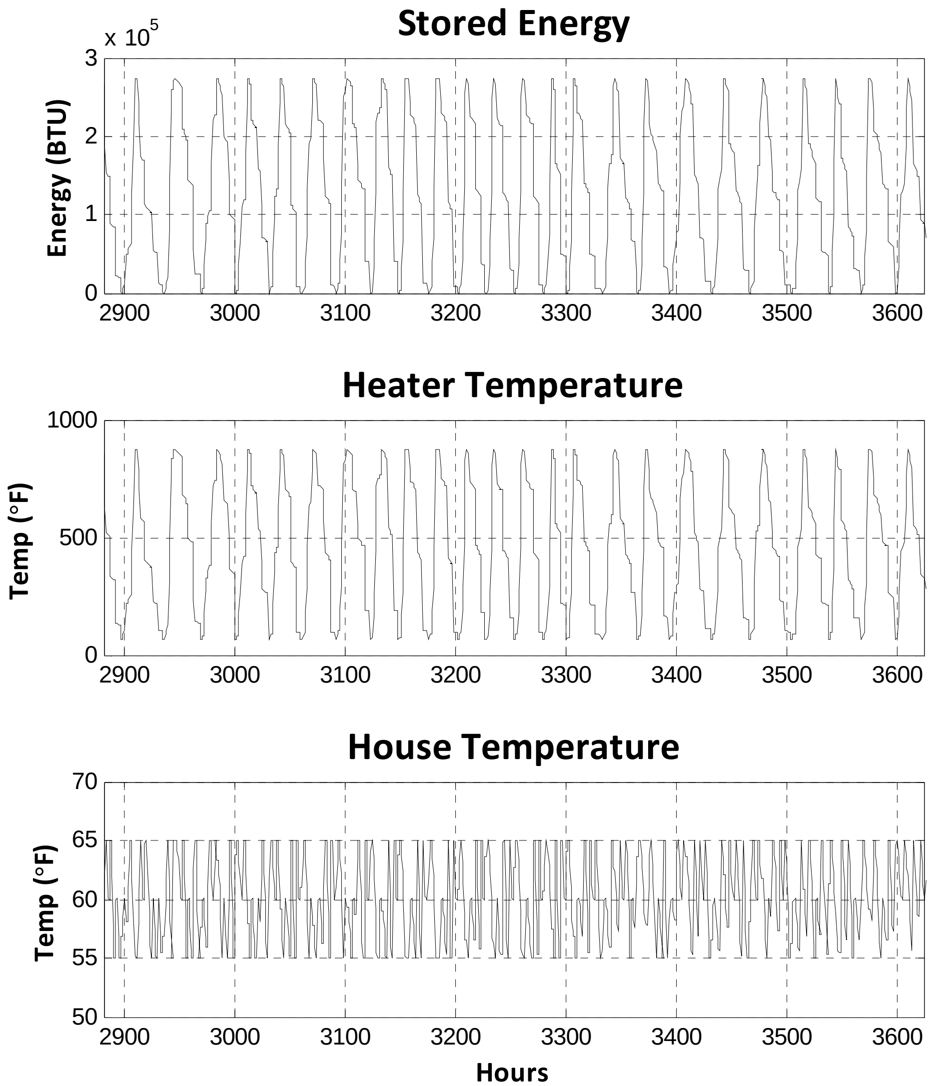

Figure 64: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Community Center in Unalakleet in May

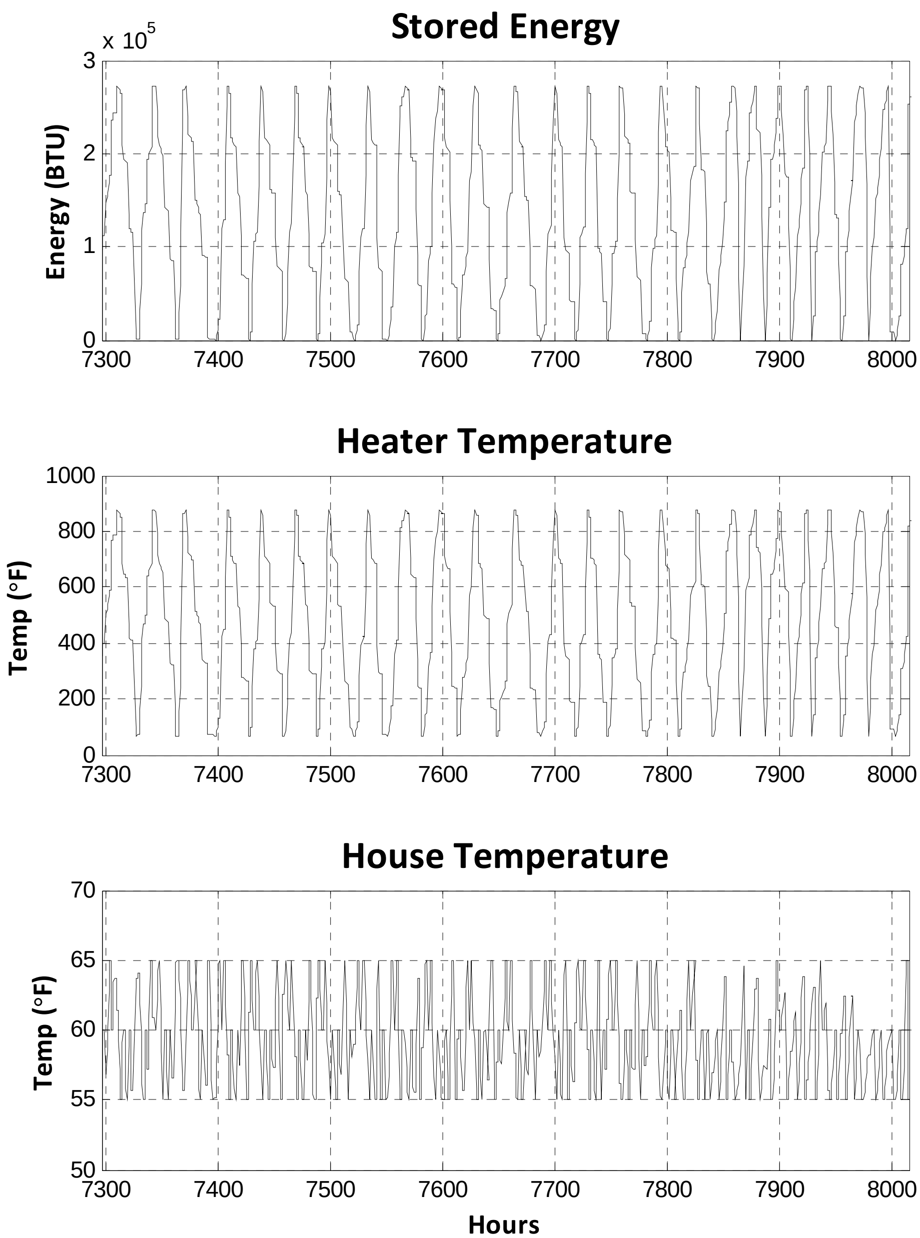

Figure 65: Energy Stored in Heater (BTU), Temperature of Heater (°F), and Temperature of House (°F), for a Community Center in Unalakleet in October

3.6.10 Higher Set Point

If the thermostat is now set to 80 °F, the small house requires 8.5 hours to charge, and the thermostat turns on 6 times, or about once every 80 minutes. It then takes 15.6 hours to discharge, during which the blower turns on 12 times, or about once every 40-50 minutes. The big house requires 35.6 hours to charge. During this time, the thermostat turns on after 36 minutes, and stays on the entire time the heater charges. It takes 7.2 hours to discharge, and the blower turns on after 45 minutes, and stays on the entire time. The community center requires two heaters to meet the heating load. They take 28.6 hours to charge, and the thermostat turns on after 54 minutes, stays on for 27 hours, and turns off. It takes 7.4 hours to discharge, during which time the blower turns on after 56 minutes and stays on the rest of the time.

3.6.11 Lower Set Point

When the thermostat is set to 55 °F, the house charges in 7.3 hours, during which time the thermostat turns on eight times, or about once every 42 minutes. It takes 23 hours to discharge, during which time the blower turns on 27 times, or once every 50 minutes. The big house requires 12.27 hours to charge, and the thermostat turns on four times, or approximately once every 3 hours. It takes 10.2 hours to discharge, during which time the blower turns on four times, or about once every 2.5 hours. The community center requires 9.45 hours to charge, during which time, the thermostat turns on three times: once after 90 minutes for 10 minutes, and then every 120 minutes. It takes 12 hours to discharge, during which time the blower turns on four times, once after 100 minutes for 20 minutes, and then at 150 minute intervals.

The times to charge and discharge for the higher and lower set points are given in Table 8.

Table 8: Time to Charge and Discharge Three Buildings at Different Temperature Set Points (Hours)

Building	Temperature Set Points					
	80 °F		60 °F		55 °F	
	Charge	**Discharge**	**Charge**	**Discharge**	**Charge**	**Discharge**
Small House	8.5	15.6	7.6	21	7.3	23
Big House	35.6	7.2	14.2	9.07	12.3	10.2
Community Center (2 heaters)	28.6	7.4	12.6	8	9.5	12

An important point to note is that the small house requires more time to discharge than to charge in all three cases. This is because the smaller thermal mass requires less energy to heat, so the heater losing heat to the room appreciably contributes to the temperature control. The small house therefore requires the blower to be turned on less often and for shorter periods of time.

Obviously, high thermostatic set points require more energy than low ones, and require more time to charge. Since the heat transfer function for insulative losses is based on the temperature difference between the inside and outside temperatures, the higher the temperature difference, the greater the rate of heat transfer. A greater rate of heat transfer translates to a much greater total amount of energy required to heat a building, and a greater amount of time spent heating the building.

Chapter 4: Masonry Electrothermal Heating and Storage Scenarios

The purpose of the electrothermal heating and storage models presented in Chapter 3 is to determine the optimal method to meet the heating demand of the houses and community buildings in a remote Alaska community using electricity from wind. The best way to do this is to determine how much energy is required to heat a home and its water supply using various methods, and the cost of generating this energy under various conditions. These conditions include availability of wind power, outdoor and indoor temperatures, and the insulation value of the buildings while using the standard heating source (Toyo Stove) as a backup. The annual cost of heating houses and community buildings were determined using the outputs from the model which include the energy stored, energy dissipated, and the inside temperature. A further economic analysis determines the payback, net present value, and cost of energy for a range of heating oil costs.

4.1 Annual Simulations for Different Buildings and Set Points

To test the accuracy of the Simulink® models, simulations were performed over a full year using actual ambient temperature profiles. Various buildings were modeled including a small house, a large house, and a community center. A switch in the model representing a thermostatic sensor turns on voltage when the heater is discharged and turns off voltage when the heater is charged.

4.2 Test Cases

The communities of Kongiganak and Unalakleet are modeled using various methods of heating buildings. Ultimately, the goal is to determine which heating method is best from an economical perspective based on displaced fuel and electricity savings. The five heating methods are:

1. Toyo stove working alone
2. Steffes heater charged with only the diesel electric generator
3. Steffes heater charged with only wind
4. Steffes heater charged with wind and a diesel generator
5. Steffes heater charged with only wind, and a Toyo stove to provide backup heat

The Kongiganak wind-diesel system consists of five wind turbines, and four John Deere diesel electric generators which generate energy at a rate of 82 kBTU/gal. The wind turbines create an excess of 2.9211×10^9 BTU annually. Unalakleet has six wind turbines and four diesel generators. Its wind turbines create an excess of 1.14×10^6 BTU annually.

4.2.1 Case 1: Heating with Toyo Stove

A model for a Toyo Stove (oil heater) is shown in Figure 66. The annual demanded temperature and outside temperatures are the inputs to the model.

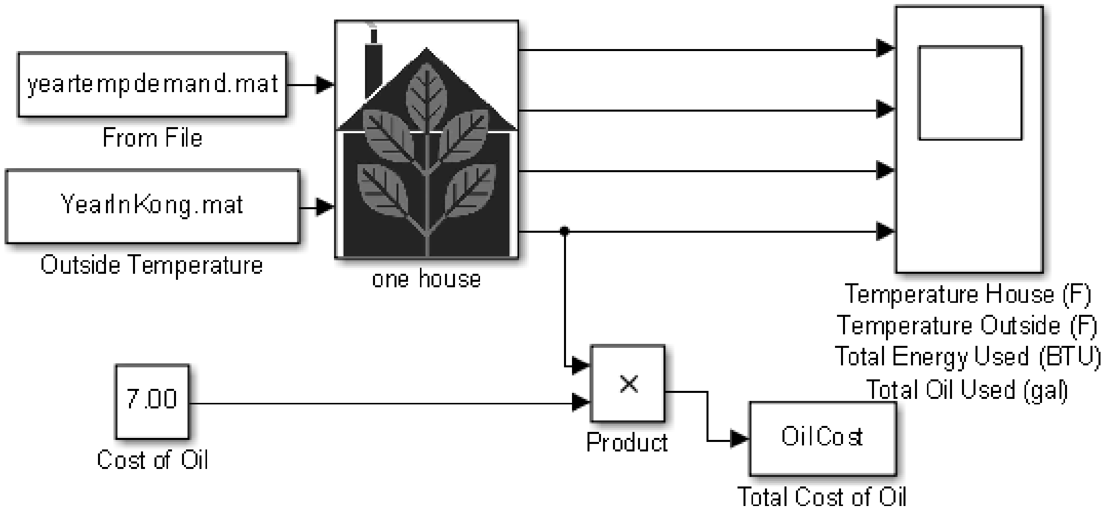

Figure 66: A Toyo Stove Heating Model for a House

Figure 67 shows the “One House” model as it takes its temperature inputs, and integrates them with the aforementioned “Oil Heater Model” (shown in Figure 21), “Losses: House to Environment” (shown in Figure 19), and “Heat Stored in House” (shown in Figure 18) models.

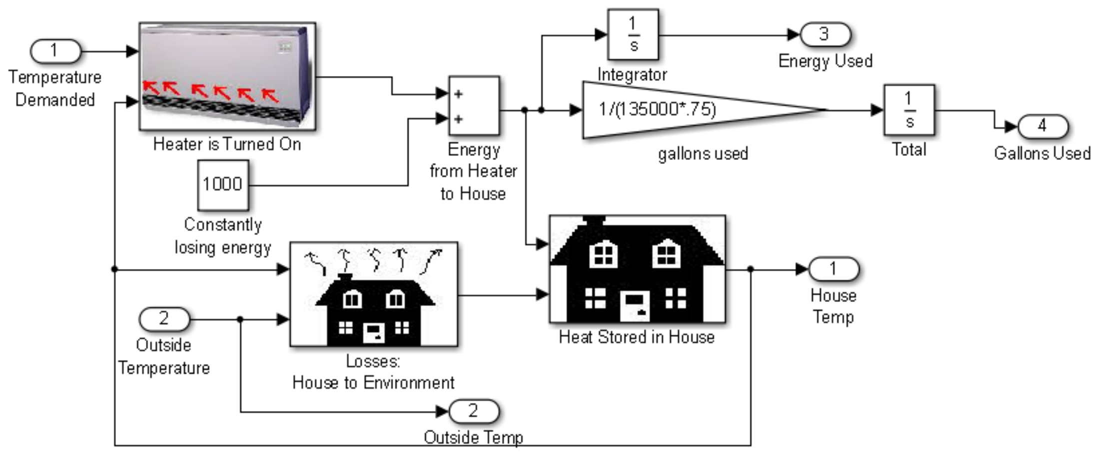

Figure 67: 'One House' Subsystem

An important part of the model is the type and heating value of heating oil used in the Toyo stove. This model uses #2 heating fuel, which supplies 138,500 BTU/gallon [13]. Table 9 provides the annual amount of energy required to heat each type of building, the annual gallons of heating oil, and the annual cost of heating for #1 heating oil costs ranging from $4.00 to $11.00 per gallon in increments of $0.25.

Table 9: Cost of Heating Various Facilities with Heating Oil (#2 Fuel)

	Small House	**Big House**	**Community Center**
MBTU	**30.57**	**70.18**	**130.2**
Gallons	**253.70**	**582.43**	**1080.54**
$4.00	$1,014.81	$2,329.72	$4,322.17
$4.25	$1,078.24	$2,475.33	$4,592.31
$4.50	$1,141.67	$2,620.94	$4,862.44
$4.75	$1,205.09	$2,766.55	$5,132.58
$5.00	$1,268.52	$2,912.15	$5,402.71
$5.25	$1,331.94	$3,057.76	$5,672.85
$5.50	$1,395.37	$3,203.37	$5,942.99
$5.75	$1,458.79	$3,348.98	$6,213.12
$6.00	$1,522.22	$3,494.58	$6,483.26
$6.25	$1,585.65	$3,640.19	$6,753.39
$6.50	$1,649.07	$3,785.80	$7,023.53
$6.75	$1,712.50	$3,931.41	$7,293.66
$7.00	$1,775.92	$4,077.02	$7,563.80
$7.25	$1,839.35	$4,222.62	$7,833.94
$7.50	$1,902.78	$4,368.23	$8,104.07
$7.75	$1,966.20	$4,513.84	$8,374.21
$8.00	$2,029.63	$4,659.45	$8,644.34
$8.25	$2,093.05	$4,805.05	$8,914.48
$8.50	$2,156.48	$4,950.66	$9,184.61
$8.75	$2,219.91	$5,096.27	$9,454.75
$9.00	$2,283.33	$5,241.88	$9,724.88
$9.25	$2,346.76	$5,387.48	$9,995.02
$9.50	$2,410.18	$5,533.09	$10,265.16
$9.75	$2,473.61	$5,678.70	$10,535.29
$10.00	$2,537.03	$5,824.31	$10,805.43
$10.25	$2,600.46	$5,969.92	$11,075.56
$10.50	$2,663.89	$6,115.52	$11,345.70
$10.75	$2,727.31	$6,261.13	$11,615.83
$11.00	$2,790.74	$6,406.74	$11,885.97

4.2.1.1 Kongiganak Results for Test Case 1

When every house in Kongigagnak is heated with a Toyo Oil Miser stove, at 87% efficiency, the small house is heated with 29.1 MBTU, or 8528.36kWh of energy. Plots of the house temperature (°F), outside temperature (°F), amount of energy used (BTU), and quantity of oil used (gallons) are shown in Figure 68. The annual average outdoor temperature is 31.9 °F. This requires 248 gallons of fuel, the annual cost of which can range from $1,240 when heating oil costs $5.00/gallon, for a COE of $42.61/MBTU, or $0.15/kWh. When heating oil costs reach $21.00/gallon, the annual cost is $5,208, with a COE of $178.97/MBTU, or $0.61/kWh.

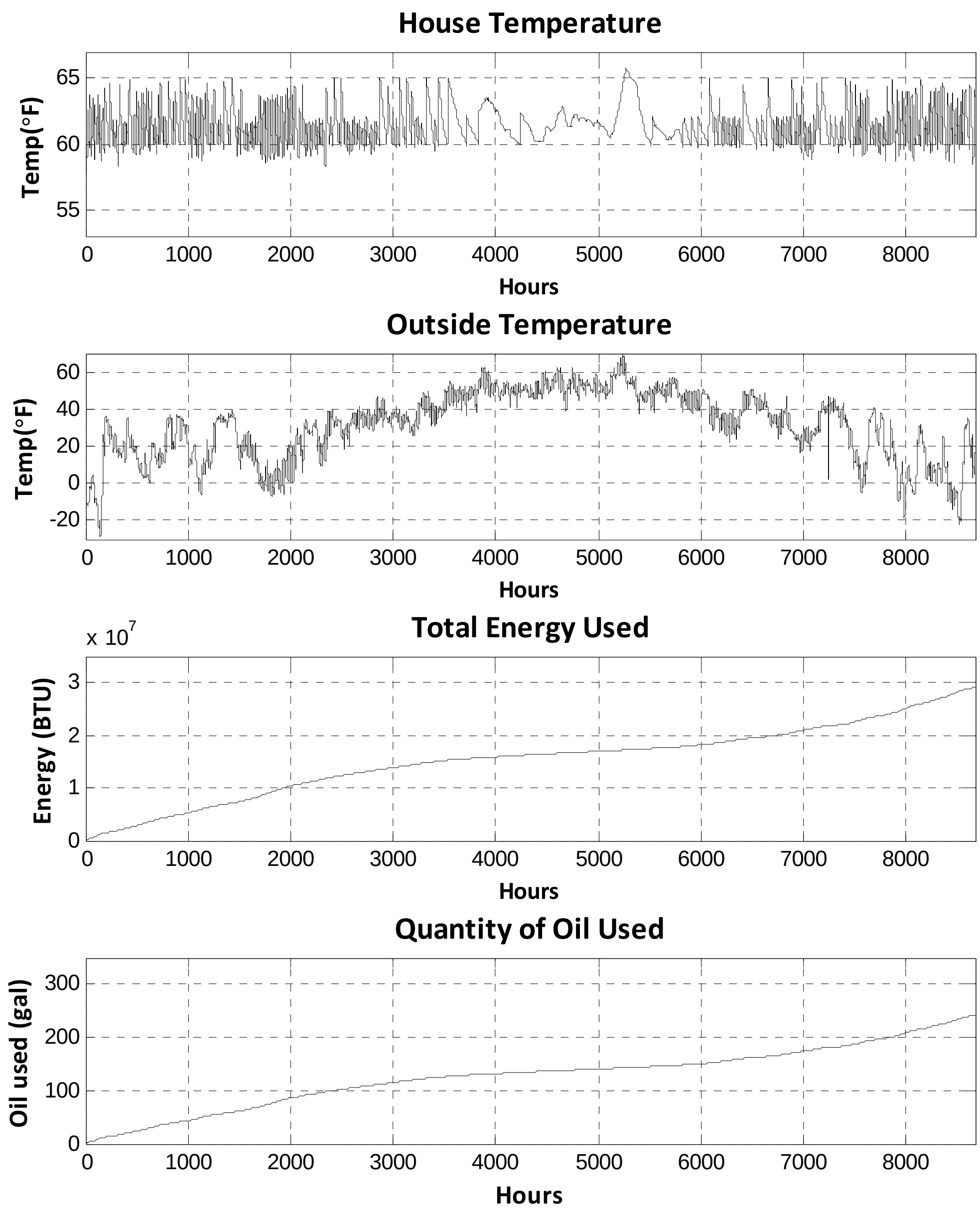

Figure 68: Heating Kongiganak for One Year with a Toyo Stove: House Temperature (°F), Outside Temperature (°F), Amount of Energy Used (BTU), and Quantity of Oil Used (Gallons)

4.2.1.2 Unalakleet Results for Test Case 1

Unalakleet requires 267 gallons of heating oil to provide 31.3 MBTU per house, or 9173 kWh of energy. Plots of the house temperature (°F), outside temperature (°F), amount of energy used (BTU), and quantity of oil used (Gallons) for Test Case #1 at Unalakleet are given in Figure 69. Energy used is higher than Kongiganak because the average outdoor temperature is lower at 28.1°F. When heating oil is $5.00/gallon, the cost of heating one house is $1,540.00, with a COE of $51.20/MBTU, or $0.17/kWh. When heating oil costs $21.00/gallon, heating a house costs $6,468 annually, and the COE is $215.03/MBTU or $0.71/kWh.

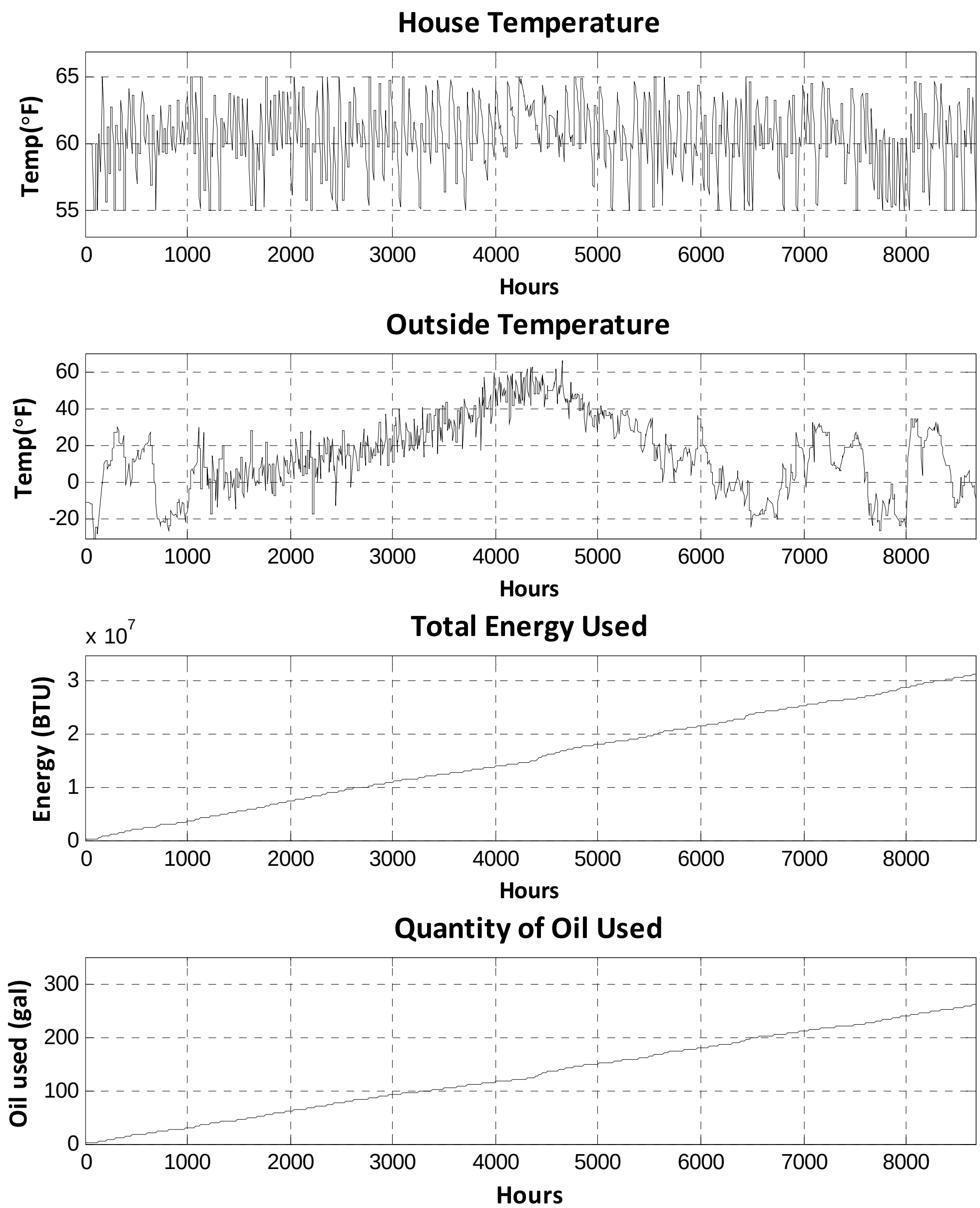

Figure 69: Heating Unalakleet for One Year with a Toyo Stove: House Temperature (°F), Outside Temperature (°F), Amount of Energy Used (BTU), and Quantity of Oil Used (Gallons)

Table 10 shows the results of Test Case #1 for heating a single house in Kongiganak and Unalakleet with a Toyo Stove for different costs of heating oil. The results seem to correlate well with the known costs of heating a house in these communities [26]. This is the base case, as it is the preferred method of heating the villages, so these values are the values to which every other case will be compared.

Table 10: Costs for Heating a House in Kongiganak and Unalakleet

Cost of Heating Oil	Kogniganak			Unalakleet		
	one house	COE ($/MBTU)	COE ($/kWh)	one house	COE ($/MBTU)	COE ($/kWh)
$5.00	$1,240.00	$42.61	$0.15	$1,335.00	$42.65	$0.15
$5.50	$1,364.00	$46.87	$0.16	$1,468.50	$46.92	$0.16
$6.00	$1,488.00	$51.13	$0.17	$1,602.00	$51.18	$0.17
$6.50	$1,612.00	$55.40	$0.19	$1,735.50	$55.45	$0.19
$7.00	$1,736.00	$59.66	$0.20	$1,869.00	$59.71	$0.20
$7.50	$1,860.00	$63.92	$0.22	$2,002.50	$63.98	$0.22
$8.00	$1,984.00	$68.18	$0.23	$2,136.00	$68.24	$0.23
$8.50	$2,108.00	$72.44	$0.25	$2,269.50	$72.51	$0.25
$9.00	$2,232.00	$76.70	$0.26	$2,403.00	$76.77	$0.26
$9.50	$2,356.00	$80.96	$0.28	$2,536.50	$81.04	$0.28
$10.00	$2,480.00	$85.22	$0.29	$2,670.00	$85.30	$0.29
$10.50	$2,604.00	$89.48	$0.31	$2,803.50	$89.57	$0.31
$11.00	$2,728.00	$93.75	$0.32	$2,937.00	$93.83	$0.32
$11.50	$2,852.00	$98.01	$0.33	$3,070.50	$98.10	$0.33
$12.00	$2,976.00	$102.27	$0.35	$3,204.00	$102.36	$0.35
$12.50	$3,100.00	$106.53	$0.36	$3,337.50	$106.63	$0.36
$13.00	$3,224.00	$110.79	$0.38	$3,471.00	$110.89	$0.38
$13.50	$3,348.00	$115.05	$0.39	$3,604.50	$115.16	$0.39
$14.00	$3,472.00	$119.31	$0.41	$3,738.00	$119.42	$0.41
$14.50	$3,596.00	$123.57	$0.42	$3,871.50	$123.69	$0.42
$15.00	$3,720.00	$127.84	$0.44	$4,005.00	$127.96	$0.44
$15.50	$3,844.00	$132.10	$0.45	$4,138.50	$132.22	$0.45
$16.00	$3,968.00	$136.36	$0.47	$4,272.00	$136.49	$0.47
$16.50	$4,092.00	$140.62	$0.48	$4,405.50	$140.75	$0.48
$17.00	$4,216.00	$144.88	$0.49	$4,539.00	$145.02	$0.49
$17.50	$4,340.00	$149.14	$0.51	$4,672.50	$149.28	$0.51
$18.00	$4,464.00	$153.40	$0.52	$4,806.00	$153.55	$0.52
$18.50	$4,588.00	$157.66	$0.54	$4,939.50	$157.81	$0.54
$19.00	$4,712.00	$161.92	$0.55	$5,073.00	$162.08	$0.55
$19.50	$4,836.00	$166.19	$0.57	$5,206.50	$166.34	$0.57
$20.00	$4,960.00	$170.45	$0.58	$5,340.00	$170.61	$0.58
$20.50	$5,084.00	$174.71	$0.60	$5,473.50	$174.87	$0.60
$21.00	$5,208.00	$178.97	$0.61	$5,607.00	$179.14	$0.61

4.2.2 Case 2: Steffes Heater Powered by Diesel Electric Generation

Another test case modeled is when the only method of heating the house is the Steffes heater, and the only method of powering the Steffes heater is with electricity from diesel electric generators. This method is obviously quite inefficient and costly, but gives another baseline for cost. The model, the 'One House' subsystem and the 'Total Cost' subsystem, are shown in Figure 70 through Figure 72.

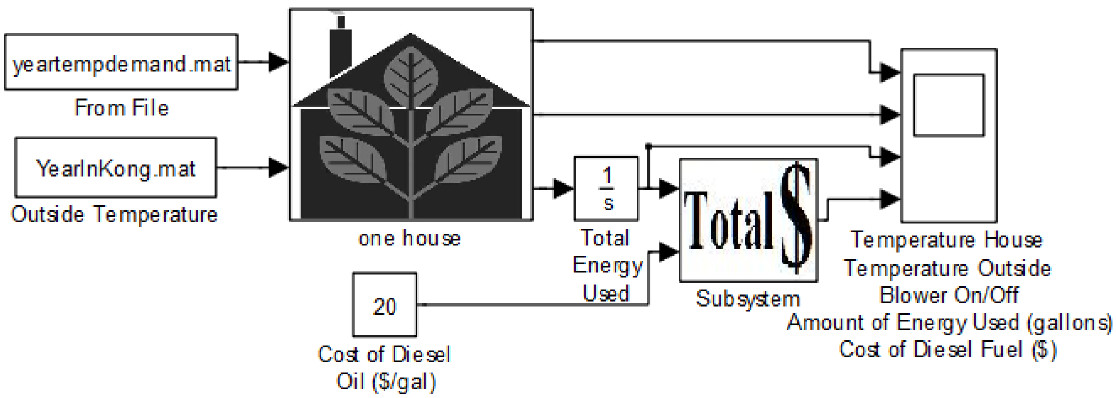

Figure 70: Charging Steffes Heater Model for House with Diesel Electric Generators

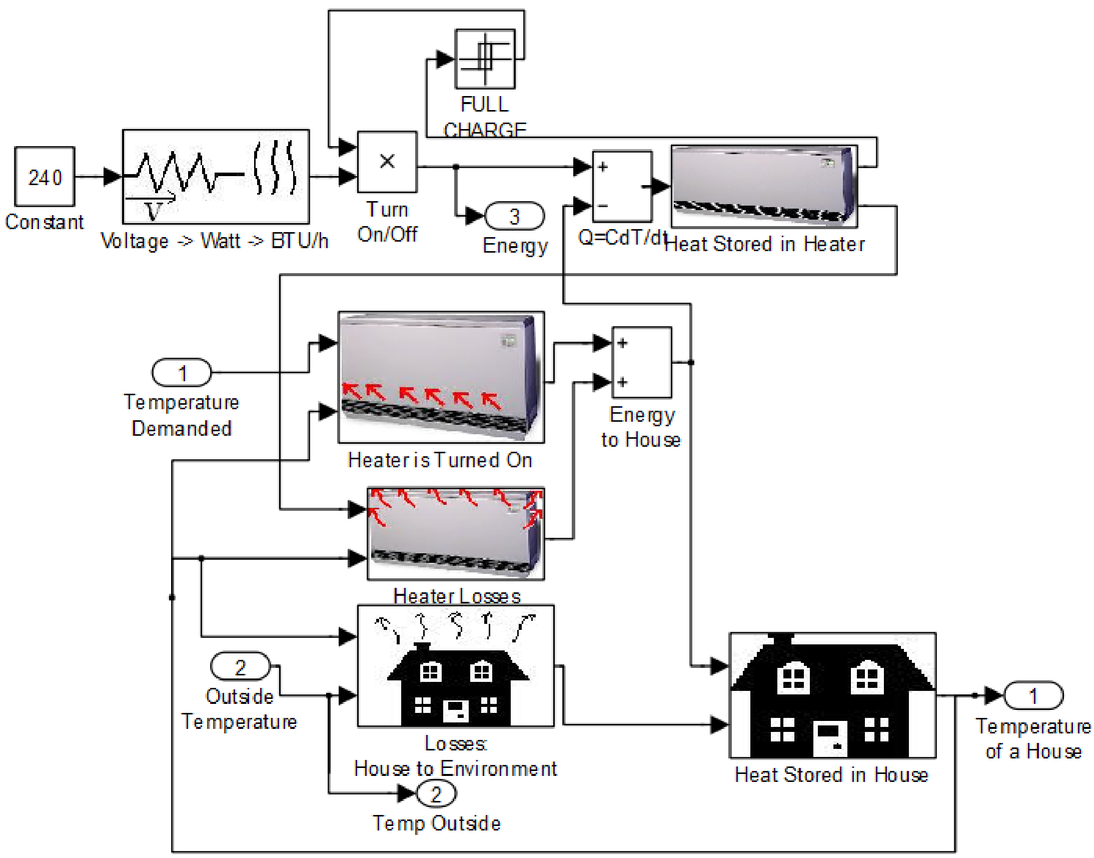

Figure 71: 'One House' Subsystem

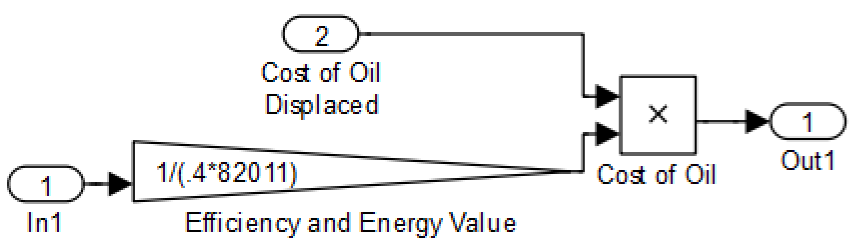

Figure 72: 'Total Cost' Subsystem

4.2.2.1 Kongiganak Results for Test Case 2

In Kongiganak, 28.4 MBTU of energy and 346.7 gallons of diesel fuel are required to keep the Steffes adequately charged and the houses at 60 °F. Plots of the house temperature (°F), outside temperature (°F), amount of energy used (BTU), and quantity of oil (Gallons) used for Test Case #2 at Kongiganak are shown in Figure 73. When diesel fuel costs $5.00 per gallon, the annual cost of heating is $1733.50. The COE is $61.04/MBTU, or $0.21/kW. At $21.00/gallon, the total cost is $7,280.70, and the COE is $256.36/MBTU, or $0.87/kWh.

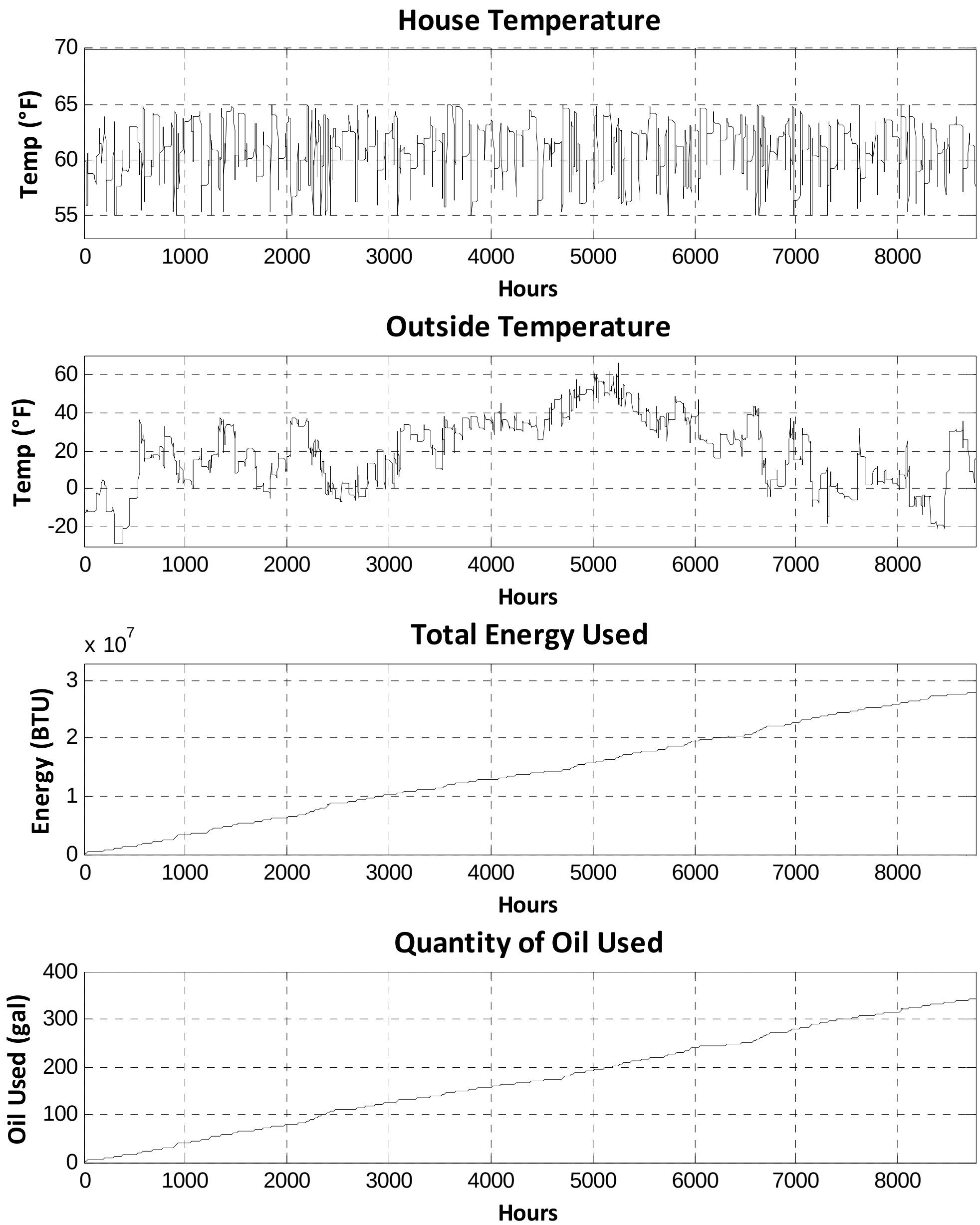

Figure 73: Heating a House in Kongiganak with Diesel Electric Generation Powering a Steffes: House Temperature (°F), Outside Temperature (°F), Total Energy Used (BTU), and Quantity of Oil Used (Gallons)

4.2.2.2 Unalakleet Results for Test Case 2

In Unalakleet, 31.4 MBTU of energy, provided by 382.9 gallons of diesel fuel are required to maintain a comfortable environment. At $5.00/gallon, it costs $1,914 to heat a house annually, with a COE of $60.96/MBTU or $0.21/kWh. At $21.00/gallon, it costs $8,041 to heat a house, with a COE of $256.04/MBTU, or $0.87/kWh. Since this is the least cost effective system and requires a system overhaul, this case will not be considered further. Figure 74 shows plots of the house temperature (°F), outside temperature (°F), amount of energy used (BTU), and quantity of oil used (Gallons) for Test Case #2 at Unalakleet.

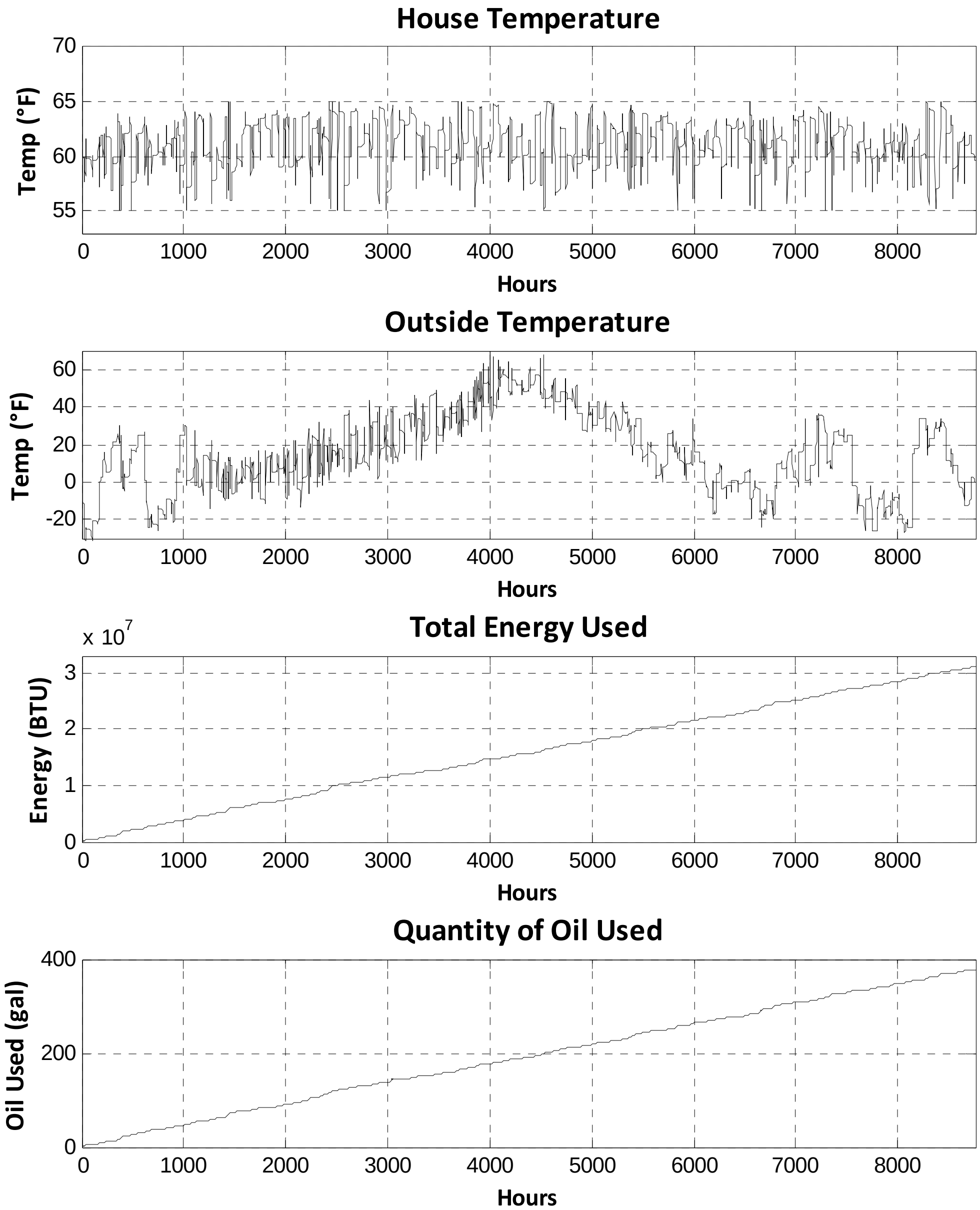

Figure 74: Heating a House in Unalakleet with Diesel Electric Generation Powering a Steffes: House Temperature (°F), Outside Temperature (°F), Total Energy Used (BTU), and Quantity of Oil Used (Gallons)

Table 11 shows the results of Test Case #2 for heating a single house in Kongiganak and Unalakleet with a Steffes unit powered by diesel electric generation for different costs of fuel oil. The results indicate that per unit of electricity heating with diesel is 13-20% more expensive than heating with heating oil. It is known that this method of heating is inefficient since burning diesel fuel to create electricity for driving resistive heating results in a lower efficiency than burning heating oil directly due to the additional energy conversion.

Table 11: Costs for Heating a House in Unalakleet and Kongiganak with Steffes Unit Powered by Diesel-Electric Generation

Cost of Diesel ($/gal)	Kongiganak			Unalakleet		
	one house	COE ($/MBTU)	COE ($/kWh)	one house	COE ($/MBTU)	COE ($/kWh)
$5.00	$1,735.00	$61.09	$0.21	$1,915.00	$60.98	$0.21
$5.50	$1,908.50	$67.20	$0.23	$2,101.00	$66.90	$0.23
$6.00	$2,082.00	$73.31	$0.25	$2,292.00	$72.98	$0.25
$6.50	$2,255.50	$79.42	$0.27	$2,483.00	$79.06	$0.27
$7.00	$2,429.00	$85.53	$0.29	$2,674.00	$85.15	$0.29
$7.50	$2,602.50	$91.64	$0.31	$2,865.00	$91.23	$0.31
$8.00	$2,776.00	$97.75	$0.33	$3,056.00	$97.31	$0.33
$8.50	$2,949.50	$103.86	$0.35	$3,247.00	$103.39	$0.35
$9.00	$3,123.00	$109.96	$0.38	$3,438.00	$109.47	$0.37
$9.50	$3,296.50	$116.07	$0.40	$3,629.00	$115.55	$0.39
$10.00	$3,470.00	$122.18	$0.42	$3,820.00	$121.64	$0.42
$10.50	$3,643.50	$128.29	$0.44	$4,011.00	$127.72	$0.44
$11.00	$3,817.00	$134.40	$0.46	$4,202.00	$133.80	$0.46
$11.50	$3,990.50	$140.51	$0.48	$4,393.00	$139.88	$0.48
$12.00	$4,164.00	$146.62	$0.50	$4,584.00	$145.96	$0.50
$12.50	$4,337.50	$152.73	$0.52	$4,775.00	$152.05	$0.52
$13.00	$4,511.00	$158.84	$0.54	$4,966.00	$158.13	$0.54
$13.50	$4,684.50	$164.95	$0.56	$5,157.00	$164.21	$0.56
$14.00	$4,858.00	$171.06	$0.58	$5,348.00	$170.29	$0.58
$14.50	$5,031.50	$177.17	$0.60	$5,539.00	$176.37	$0.60
$15.00	$5,205.00	$183.27	$0.63	$5,730.00	$182.46	$0.62
$15.50	$5,378.50	$189.38	$0.65	$5,921.00	$188.54	$0.64
$16.00	$5,552.00	$195.49	$0.67	$6,112.00	$194.62	$0.66
$16.50	$5,725.50	$201.60	$0.69	$6,303.00	$200.70	$0.68
$17.00	$5,899.00	$207.71	$0.71	$6,494.00	$206.78	$0.71
$17.50	$6,072.50	$213.82	$0.73	$6,685.00	$212.86	$0.73
$18.00	$6,246.00	$219.93	$0.75	$6,876.00	$218.95	$0.75
$18.50	$6,419.50	$226.04	$0.77	$7,067.00	$225.03	$0.77
$19.00	$6,593.00	$232.15	$0.79	$7,258.00	$231.11	$0.79
$19.50	$6,766.50	$238.26	$0.81	$7,449.00	$237.19	$0.81
$20.00	$6,940.00	$244.37	$0.83	$7,640.00	$243.27	$0.83
$20.50	$7,113.50	$250.48	$0.85	$7,831.00	$249.36	$0.85
$21.00	$7,287.00	$256.58	$0.88	$8,022.00	$255.44	$0.87

4.2.3 Case 3: Steffes Heater Powered from Wind Energy Only

A case is run where only the Steffes is used to heat the house, and it is powered only from wind energy. If the energy in the Steffes is depleted, no other method of domestic heating is used. The purpose of running this scenario is to determine whether it is possible to power a Steffes entirely from wind energy.

4.2.3.1 Case 3: Kongiganak

In Kongiganak, 2,900 MBTU is produced in excess of that which can be used, or 38.16 MBTU per house, of which only 17.11 MBTU are usable. When wind energy is modeled as having a COE of \$0.15/kWh, or \$43.96/MBTU, this effectively displaced \$732.85 of energy, or 146 gallons of #2 heating oil. The houses are kept comfortable for 3 months of the year, but do not consistently reach a reasonable room temperature throughout the fall, winter and spring. Plots of the house temperature (°F), outside temperature (°F), amount of energy used (BTU), and quantity of oil displaced (Gallons) for Test Case #3 at Kongiganak are shown in Figure 75. The temperature of the house reaches as low as 17 °F, indicating that simply using wind energy to power a Steffes heating unit would not be sufficient to serve the heating needs of a house in Kongiganak.

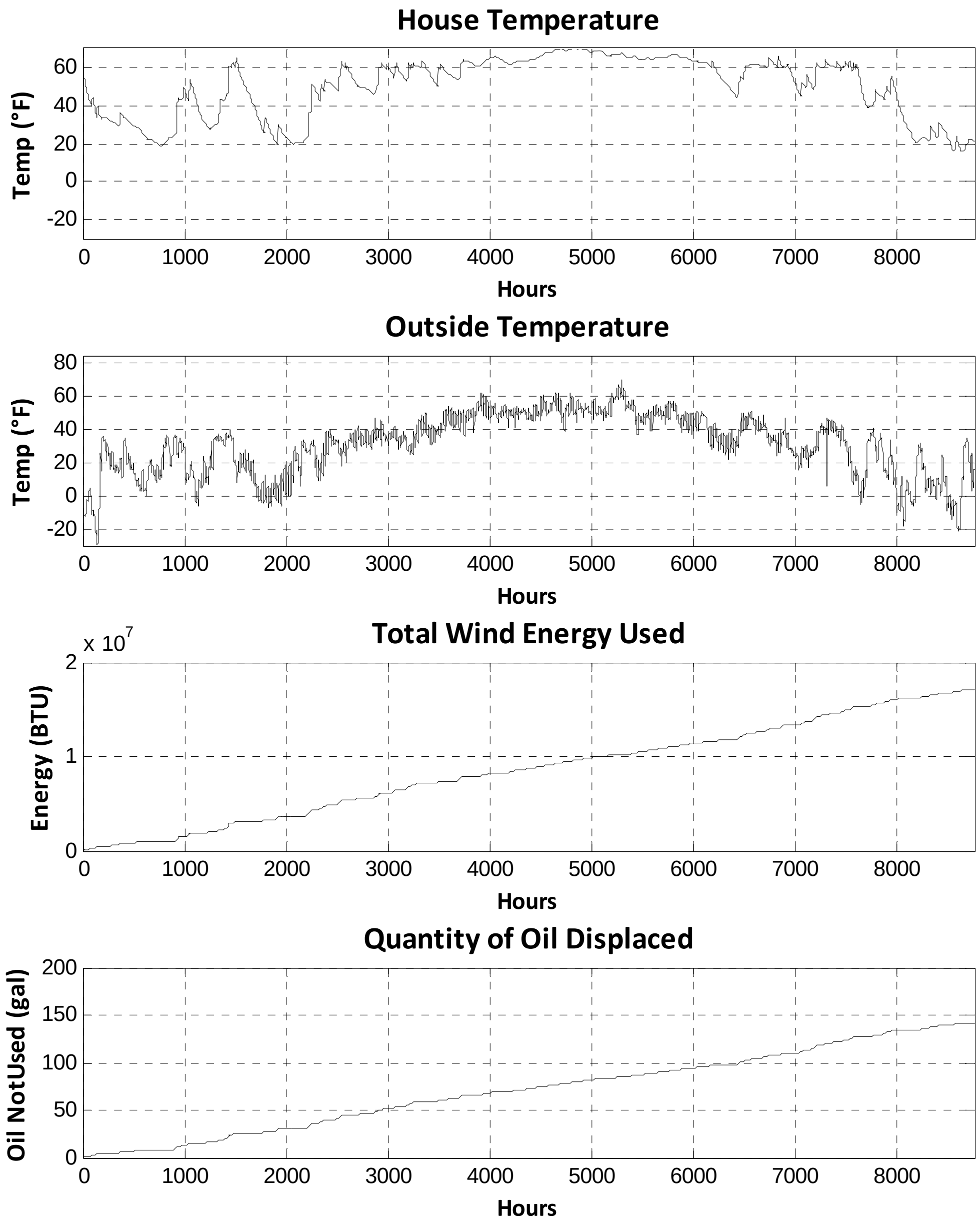

Figure 75: Heating a House in Kongiganak with a Steffes Powered by Wind Energy: House Temperature (°F), Outside Temperature (°F), Total Wind Energy Used (BTU), and Quantity of Oil Displaced (Gallons)

4.2.3.2 Case 3: Unalakleet

Wind in Unalakleet produces 26.0 MBTU of excess electricity, or 0.1155 MBTU per house. This is certainly not enough energy to heat a house, and the Steffes heaters never fully charge, so all 0.1155 MBTU are used to heat the houses, displacing 0.00022 gallons of heating oil per house. When wind energy is modeled as having a COE of $0.15/kWh, or $43.96/MBTU, this costs $5.08. Plots of the house temperature (°F), outside temperature (°F), amount of energy used (BTU), and quantity of oil displaced (Gallons) for Test Case #3 at Unalakleet are shown in Figure 76. The house temperature reaches a low of -4 °F, and the lines representing "Total Wind Energy Used" and "Quantity of Oil Displaced" are barely visible. This indicates that simply using wind energy to power a Steffes heating unit is insufficient to serve the heating needs of a house in Unalakleet.

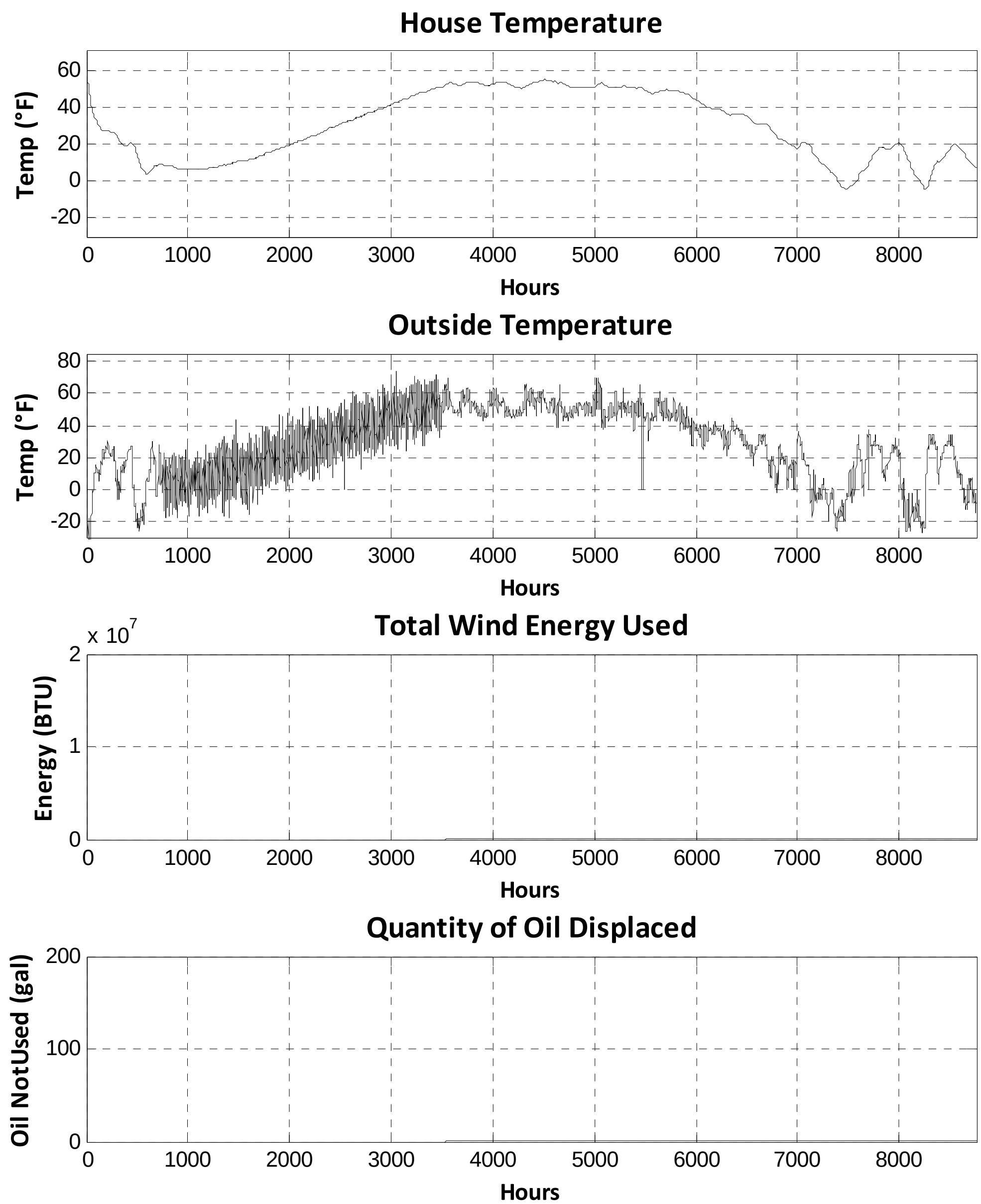

Figure 76: Heating a House in Unalakleet with a Steffes Powered by Wind Energy: House Temperature (°F), Outside Temperature (°F), Total Wind Energy Used (BTU), and Quantity of Oil Displaced (Gallons)

4.2.4 Case 4: Steffes Powered from Excess Wind with Toyo Stove for Backup Heat

The case of using a Steffes unit powered by excess wind energy with the Toyo stove for backup heat to maintain the house temperature at the set point is expected to yield the best results. Energy created by the wind turbines which is not used to generate electricity is diverted to the Steffes unit. This excess wind energy is used as needed to keep the temperature of the house at the set point. When the Steffes unit fails to provide the demanded set point temperature, the Toyo stove is used. Figure 77 and Figure 78 show the model and the voltage to BTU/h conversion subsystem for the case with the Steffes combined with the existing Toyo oil heaters.

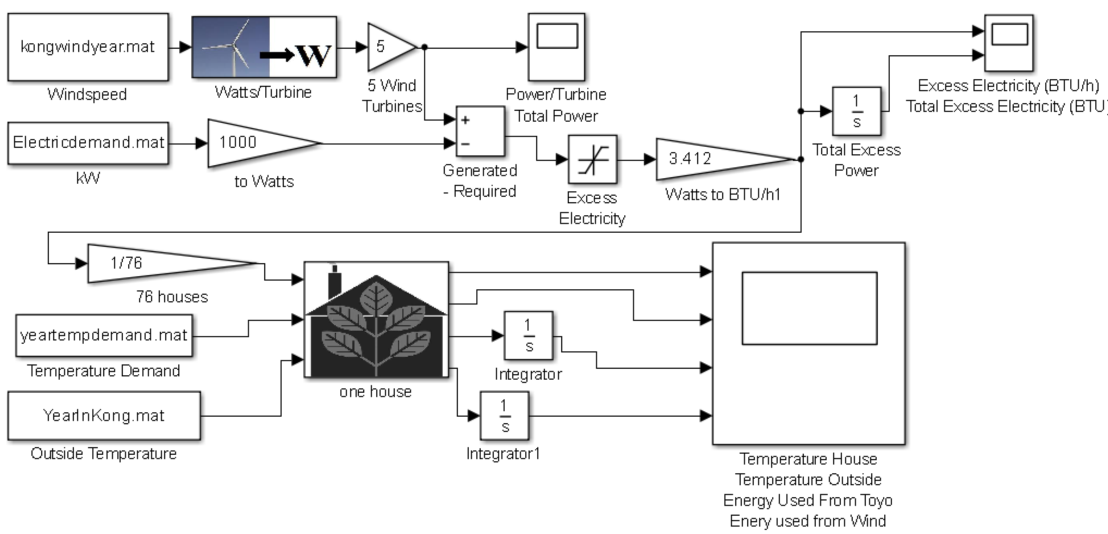

Figure 77: Model for Steffes Charging with Excess Win, Using Toyo Stove to Supplement

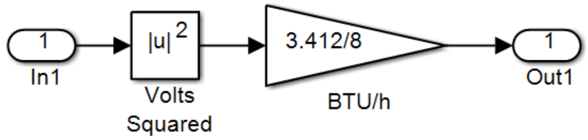

Figure 78: Voltage to BTU/h Conversion Subsystem

4.2.4.1 Case 4: Kongiganak

In Kongiganak, a total of 2,919 MBTU of excess energy is produced. Figure 79 shows plots of house temperature (°F), outside temperature (°F), amount of energy used by the Toyo (BTU), and energy used from the wind (BTU) for a house in Kongiganak. Each house uses 16.824 MBTU from the Toyo, and 12.95 MBTU from the wind. It takes 143.2 gallons of heating oil to heat the house. This saves 110.3 gallons of heating oil. When heating oil is \$5.00/gallon, the cost of heating a house is \$838 per year, netting an annual savings of \$636 over using the stove alone. At \$21.00/gallon, heating oil costs \$3,008/year, saving \$2,669 annually.

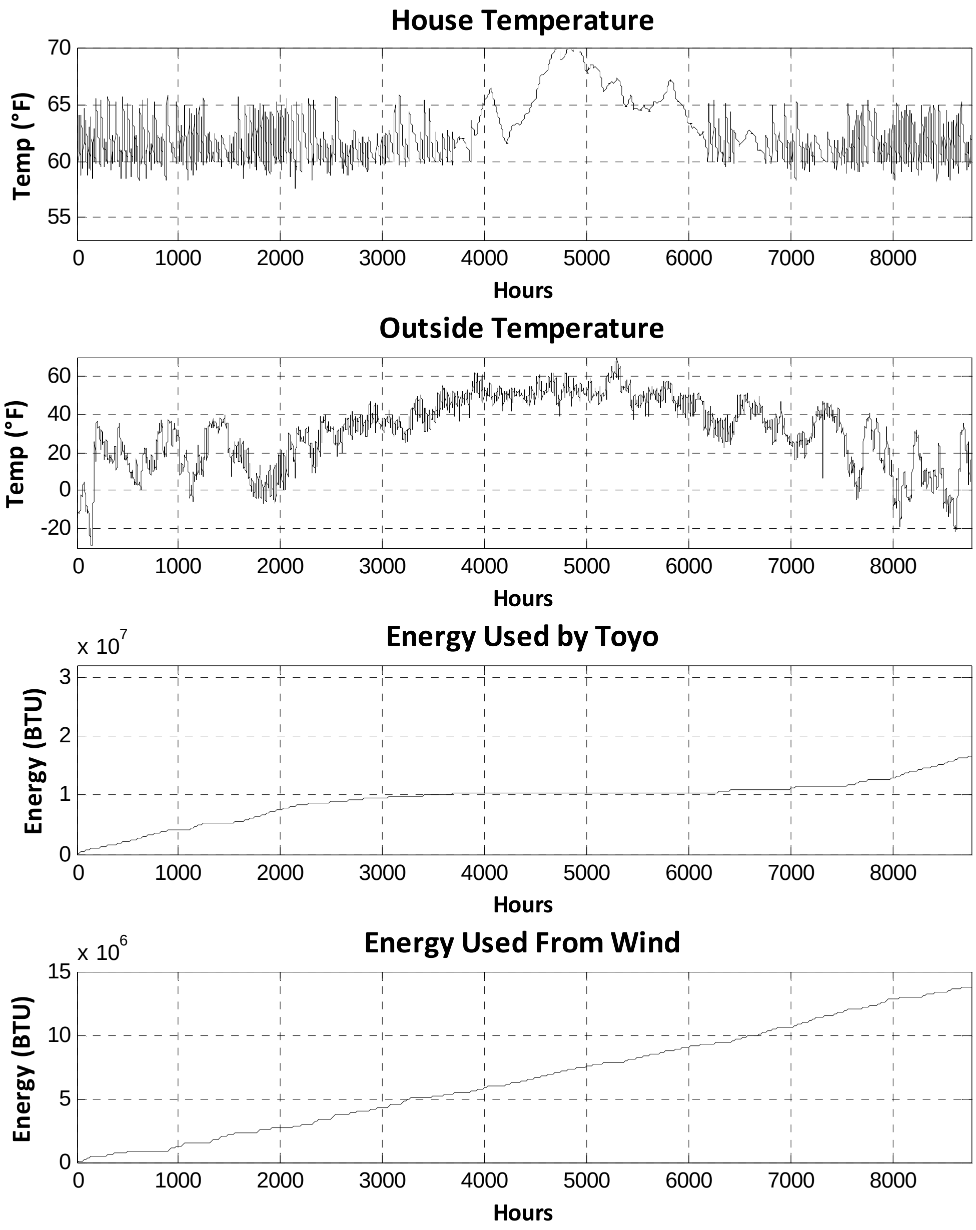

Figure 79: House Temperature (°F), Outside Temperature (°F), Amount of Energy Used by the Toyo (BTU), and Energy Used from the Wind (BTU) for a House in Kongiganak

4.2.4.2 Case 4: Unalakleet

In Unalakleet, the wind provides 1.1363 MBTU of excess energy for 225 houses, or 0.005 MBTU per house, of which, all 0.005 MBTU are consumed. Figure 80 shows plots of house temperature (°F), outside temperature (°F), amount of energy used by the Toyo (BTU), and energy used from the wind (BTU) for a house in Unalakleet. The wind energy displaced 0.0426 gallons of oil. The Toyo stove uses 266 gallons of heating oil, or 31.3 MBTU to make up the difference. When heating oil costs $5.00/gallon, the cost of heating a house is $1,332 per year, netting an annual savings of $0.21 over just the Toyo stove. When heating oil is $21.00/gallon, heating a house costs $5,596, saving $0.89/year. This solution is probably not economically viable as far as fuel savings will not offset capital cots, but it will be thoroughly analyzed as a comparison with the Kongiganak model.

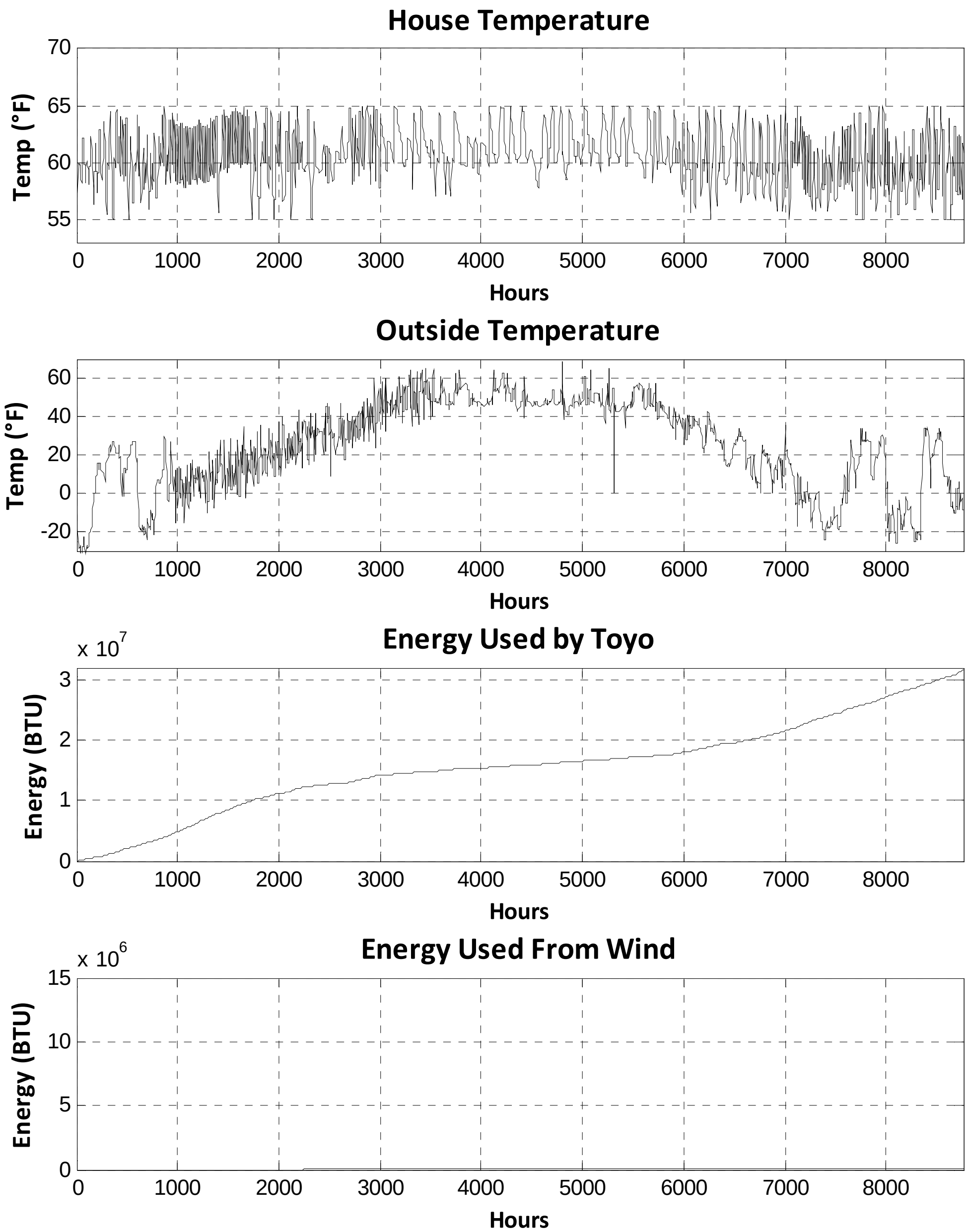

Figure 80: House Temperature (°F), Outside Temperature (°F), Amount of Energy Used by the Toyo (BTU), and Energy Used from the Wind (BTU) for a House in Unalakleet

Table 12 shows the results of Test Case #4 for heating a single house in Kongiganak and Unalakleet with a Steffes unit powered by excess wind energy working in combination with a Toyo stove to provide the heat demand for different costs of fuel oil. The results indicate that it is much cheaper, per unit of energy, to heat one's house in this manner than any previously discussed manner. To determine whether it is the cheapest method, the costs of installing new components will be compared to the fuel savings in Section 4.4.

Table 12: Costs Associated with Charging Steffes from Wind Power and Making up the Heat Demand with a Toyo Stove

Cost of Heating Oil	Kongiganak				Unalakleet			
	Gallons	29.8 MBTU	8726 kWh	Gallons Saved	Gallons	31.5 MBTU	9175 kWh	Gallons Saved
	143.24	$/MBTU	$/kWh	110.3	266.496	$/MBTU	$/kWh	0.0426
$5.00	$716.20	$24.03	$0.08	$551.50	$1,332.48	$42.57	$0.15	$0.21
$5.50	$787.82	$26.44	$0.09	$606.65	$1,465.73	$46.83	$0.16	$0.23
$6.00	$859.44	$28.84	$0.10	$661.80	$1,598.98	$51.09	$0.17	$0.26
$6.50	$931.06	$31.24	$0.11	$716.95	$1,732.22	$55.34	$0.19	$0.28
$7.00	$1,002.68	$33.65	$0.11	$772.10	$1,865.47	$59.60	$0.20	$0.30
$7.50	$1,074.30	$36.05	$0.12	$827.25	$1,998.72	$63.86	$0.22	$0.32
$8.00	$1,145.92	$38.45	$0.13	$882.40	$2,131.97	$68.11	$0.23	$0.34
$8.50	$1,217.54	$40.86	$0.14	$937.55	$2,265.22	$72.37	$0.25	$0.36
$9.00	$1,289.16	$43.26	$0.15	$992.70	$2,398.46	$76.63	$0.26	$0.38
$9.50	$1,360.78	$45.66	$0.16	$1,047.85	$2,531.71	$80.89	$0.28	$0.40
$10.00	$1,432.40	$48.07	$0.16	$1,103.00	$2,664.96	$85.14	$0.29	$0.43
$10.50	$1,504.02	$50.47	$0.17	$1,158.15	$2,798.21	$89.40	$0.30	$0.45
$11.00	$1,575.64	$52.87	$0.18	$1,213.30	$2,931.46	$93.66	$0.32	$0.47
$11.50	$1,647.26	$55.28	$0.19	$1,268.45	$3,064.70	$97.91	$0.33	$0.49
$12.00	$1,718.88	$57.68	$0.20	$1,323.60	$3,197.95	$102.17	$0.35	$0.51
$12.50	$1,790.50	$60.08	$0.21	$1,378.75	$3,331.20	$106.43	$0.36	$0.53
$13.00	$1,862.12	$62.49	$0.21	$1,433.90	$3,464.45	$110.69	$0.38	$0.55
$13.50	$1,933.74	$64.89	$0.22	$1,489.05	$3,597.70	$114.94	$0.39	$0.58
$14.00	$2,005.36	$67.29	$0.23	$1,544.20	$3,730.94	$119.20	$0.41	$0.60
$14.50	$2,076.98	$69.70	$0.24	$1,599.35	$3,864.19	$123.46	$0.42	$0.62
$15.00	$2,148.60	$72.10	$0.25	$1,654.50	$3,997.44	$127.71	$0.44	$0.64
$15.50	$2,220.22	$74.50	$0.25	$1,709.65	$4,130.69	$131.97	$0.45	$0.66
$16.00	$2,291.84	$76.91	$0.26	$1,764.80	$4,263.94	$136.23	$0.46	$0.68
$16.50	$2,363.46	$79.31	$0.27	$1,819.95	$4,397.18	$140.49	$0.48	$0.70
$17.00	$2,435.08	$81.71	$0.28	$1,875.10	$4,530.43	$144.74	$0.49	$0.72
$17.50	$2,506.70	$84.12	$0.29	$1,930.25	$4,663.68	$149.00	$0.51	$0.75
$18.00	$2,578.32	$86.52	$0.30	$1,985.40	$4,796.93	$153.26	$0.52	$0.77
$18.50	$2,649.94	$88.92	$0.30	$2,040.55	$4,930.18	$157.51	$0.54	$0.79
$19.00	$2,721.56	$91.33	$0.31	$2,095.70	$5,063.42	$161.77	$0.55	$0.81
$19.50	$2,793.18	$93.73	$0.32	$2,150.85	$5,196.67	$166.03	$0.57	$0.83
$20.00	$2,864.80	$96.13	$0.33	$2,206.00	$5,329.92	$170.28	$0.58	$0.85
$20.50	$2,936.42	$98.54	$0.34	$2,261.15	$5,463.17	$174.54	$0.60	$0.87
$21.00	$3,008.04	$100.94	$0.34	$2,316.30	$5,596.42	$178.80	$0.61	$0.89

4.2.5 Case 5: Steffes Charged from Excess Wind and Diesel Electric Generators

In Case 5, the wind charges the Steffes. When the wind power cannot keep the heater charged to meet the demand, diesel electric generators provide the power. This case is used to show the importance of powering the Steffes from wind energy. Figure 81 shows the "How Much is Stored" subsystem which quantifies the thermal energy stored in the masonry given inputs and losses.

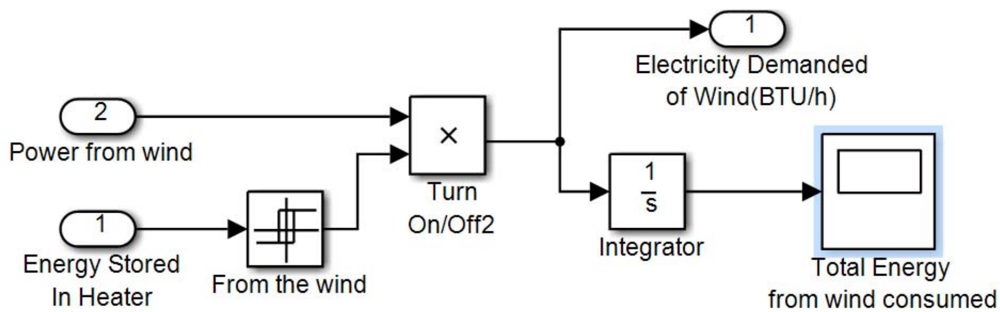

Figure 81: 'How Much is Stored' Subsystem

4.2.5.1 Case 5: Kongiganak

In Kongiganak, a total of 2,919 MBTU of excess energy is produced, or 38.41 MBTU per house. Figure 82 shows plots of house temperature (°F), outside temperature (°F), the energy demanded from diesel electric generators (BTU) and the energy consumed from the wind (BTU) for a small house in Kongiganak. The energy consumed per house from the wind is 10.3 MBTU, while 18.4 MBTU is used from the diesel electric generators. This requires 224 gallons of diesel fuel. At $5.00/gallon, the annual cost is $1,573, with a COE of $54.80/MBTU or $0.19/kWh. When diesel fuel is $21.00/gallon, the annual cost is $5,157 annually, for a COE of $180/MBTU, or $0.61/kWh.

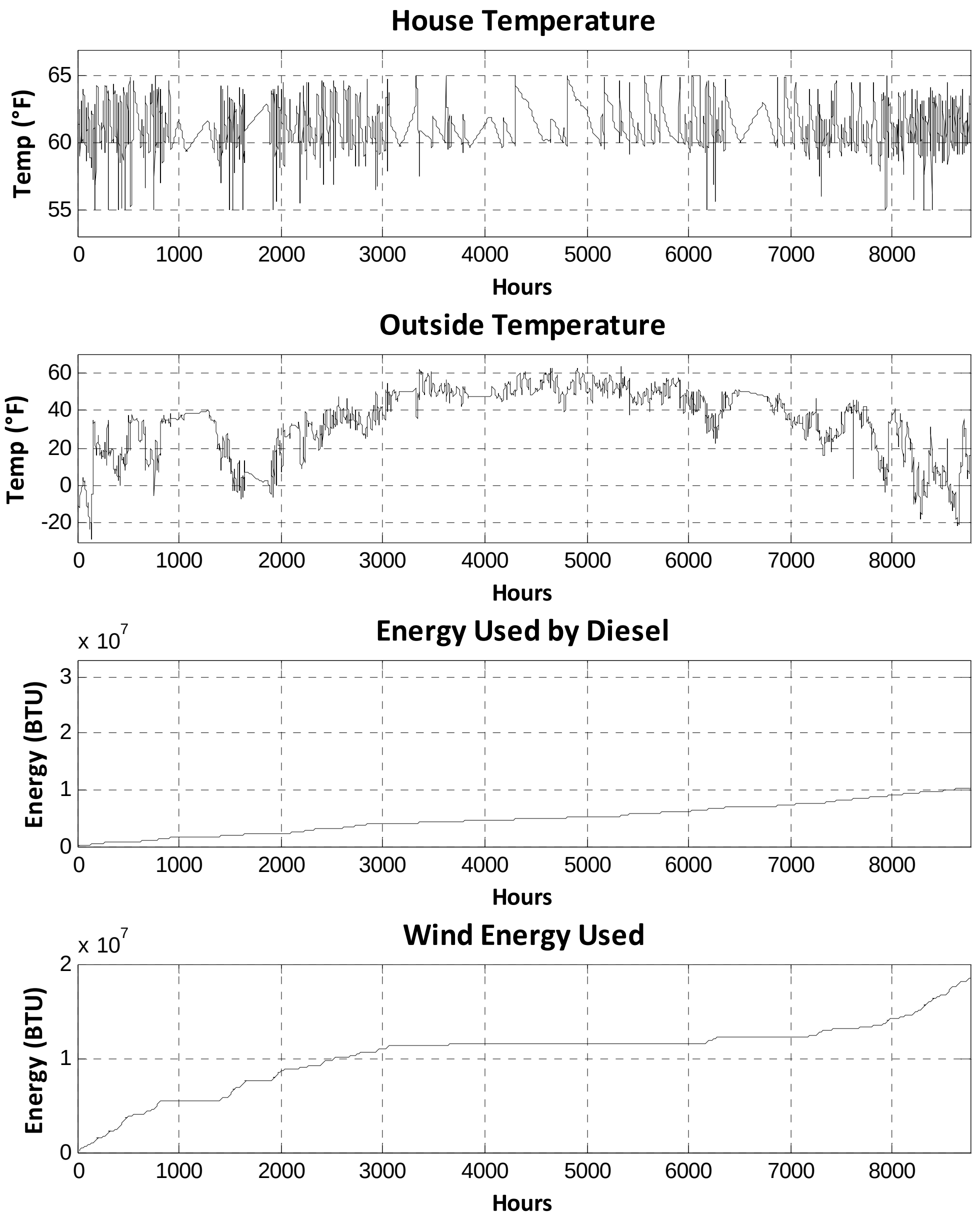

Figure 82: House Temperature (°F), Outside Temperature (°F), Wind Energy Used (BTU), and Energy Used by the Diesel Electric Generators (BTU), for a Small House in Kongiganak

4.2.5.2 Case 5: Unalakleet

In Unalakleet, 1.136 MBTU of wind energy is produced in excess of the demand. Figure 83 shows plots of house temperature (°F), outside temperature (°F), the energy demanded from diesel electric generators (BTU) and the energy consumed from the wind (BTU) for a small house in Unalakleet. For 225 houses, 0.00129 MBTU of excess wind energy is produced per house, of which all 0.00129 MBTU are consumed. Diesel generators provide 31.3 MBTU of electricity, requiring 382 gallons of diesel fuel. At \$5.00/gallon, the annual cost is \$1,910, with COEs of \$61/MBTU and \$0.21/kWh. When diesel fuel costs \$21.00/gallon, the annual cost is \$8,022, the COE is \$255/MBTU, or \$0.87/kWh.

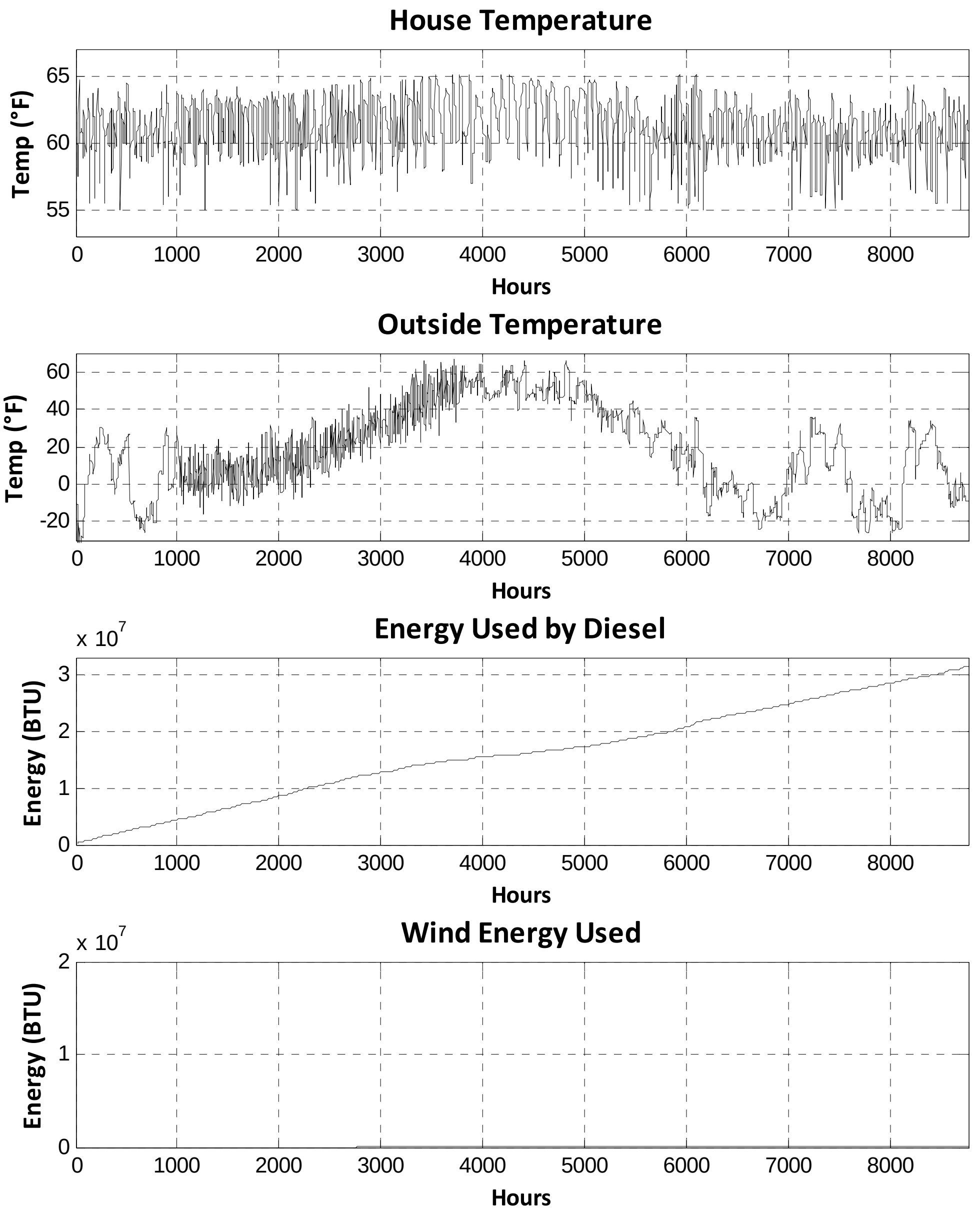

Figure 83: House Temperature (°F), Outside Temperature (°F), Wind Energy Used (BTU), and Energy Used by the Diesel Electric Generators (BTU), for a Small House in Unalakleet

Table 12 shows the results of Test Case #5 for heating a single house in Kongiganak and Unalakleet with a Steffes unit powered by excess wind energy working in combination with diesel electric generation to provide the heat demand for different costs of diesel fuel. The results indicate that this method of heating is quite expensive, and may only be considered if heating oil becomes much more expensive than diesel.

Table 13: Costs Associated with Charging Steffes from Wind Power and Making up the Difference in Heat Demand with Diesel Electric Generation

Cost of Fuel ($/gal)	**Kongiganak**			**Unalakleet**		
	Total Annual Cost	**COE ($/MBTU)**	**COE ($/kWh)**	**Total Annual Cost**	**COE ($/MBTU)**	**COE ($/kWh)**
$5.00	$1,572.69	$54.80	$0.19	$1,910.06	$60.82	$0.21
$5.50	$1,684.69	$58.70	$0.20	$2,101.06	$66.90	$0.23
$6.00	$1,796.69	$62.60	$0.21	$2,292.06	$72.98	$0.25
$6.50	$1,908.69	$66.50	$0.23	$2,483.06	$79.07	$0.27
$7.00	$2,020.69	$70.41	$0.24	$2,674.06	$85.15	$0.29
$7.50	$2,132.69	$74.31	$0.25	$2,865.06	$91.23	$0.31
$8.00	$2,244.69	$78.21	$0.27	$3,056.06	$97.31	$0.33
$8.50	$2,356.69	$82.11	$0.28	$3,247.06	$103.39	$0.35
$9.00	$2,468.69	$86.02	$0.29	$3,438.06	$109.47	$0.37
$9.50	$2,580.69	$89.92	$0.31	$3,629.06	$115.56	$0.39
$10.00	$2,692.69	$93.82	$0.32	$3,820.06	$121.64	$0.42
$10.50	$2,804.69	$97.72	$0.33	$4,011.06	$127.72	$0.44
$11.00	$2,916.69	$101.63	$0.35	$4,202.06	$133.80	$0.46
$11.50	$3,028.69	$105.53	$0.36	$4,393.06	$139.88	$0.48
$12.00	$3,140.69	$109.43	$0.37	$4,584.06	$145.97	$0.50
$12.50	$3,252.69	$113.33	$0.39	$4,775.06	$152.05	$0.52
$13.00	$3,364.69	$117.24	$0.40	$4,966.06	$158.13	$0.54
$13.50	$3,476.69	$121.14	$0.41	$5,157.06	$164.21	$0.56
$14.00	$3,588.69	$125.04	$0.43	$5,348.06	$170.29	$0.58
$14.50	$3,700.69	$128.94	$0.44	$5,539.06	$176.37	$0.60
$15.00	$3,812.69	$132.85	$0.45	$5,730.06	$182.46	$0.62
$15.50	$3,924.69	$136.75	$0.47	$5,921.06	$188.54	$0.64
$16.00	$4,036.69	$140.65	$0.48	$6,112.06	$194.62	$0.66
$16.50	$4,148.69	$144.55	$0.49	$6,303.06	$200.70	$0.68
$17.00	$4,260.69	$148.46	$0.51	$6,494.06	$206.78	$0.71
$17.50	$4,372.69	$152.36	$0.52	$6,685.06	$212.87	$0.73
$18.00	$4,484.69	$156.26	$0.53	$6,876.06	$218.95	$0.75
$18.50	$4,596.69	$160.16	$0.55	$7,067.06	$225.03	$0.77
$19.00	$4,708.69	$164.07	$0.56	$7,258.06	$231.11	$0.79
$19.50	$4,820.69	$167.97	$0.57	$7,449.06	$237.19	$0.81
$20.00	$4,932.69	$171.87	$0.59	$7,640.06	$243.28	$0.83
$20.50	$5,044.69	$175.77	$0.60	$7,831.06	$249.36	$0.85
$21.00	$5,156.69	$179.68	$0.61	$8,022.06	$255.44	$0.87

4.2.6 Summary

In comparing results, it can be useful to see the prices per unit energy at a glance. Table 14 shows the prices of energy for the four effective methods of heating (cases 1, 2, 4, and 5), before the start-up costs are considered. cases 1 and 4 compare heating oil, while cases 2 and 5 compare costs of heating oil. case 1 is the only case that does not involve installing new appliances.

From Table 13, it is clear that case 2 is superior to case 5 in Kongiganak and Unalakleet: if the Steffes unit is to be installed in a house, then wind power should be harnessed to charge it, and not diesel electricity. In Unalakleet, the wind levels are so low that the wind turbines do not create enough excess energy that it can be harnessed. This was expected, as it is known that offsetting some of the heating load with wind power will increase the system efficiency.

Since cases 2, 3, 4, and 5 require expensive capital improvements, they should only be implemented if the costs of those improvements are offset by the savings. Cases 1 and 4 can be compared at the same heating oil prices for various interest rates when the purchase price and installation costs of the Steffes units are known. Once the superior of the two cases is determined, the unit energy cost can be compared to case 5 at different costs of heating oil and diesel oil. Table 14 shows that, in Kongiganak, case 4 is superior to case 5 for all cases where heating oil and diesel oil cost the same amount, in all situations where heating oil costs less than \$11.50/gallon in, and in all cases where Diesel costs more than \$11.00/gallon. In Unalakleet, the scenario is better for case 4 when the two fuels cost the same, when heating oil costs less than \$6.00/gallon, and when diesel oil costs more than \$11.00/gallon in Kongiganak, and \$15.00/gallon in Unalakleet. From this, it is determined that if the Steffes unit is installed, it is better to make up the heating deficit from using wind energy with a Toyo stove burning heating oil than with the Steffes heater operating on diesel oil.

Table 14: Comparing Prices of Each Case at Each Cost of Oil ($/kWh)

Cost of Oil	Case 1 (Heating Oil)		Case 2 (Diesel Oil)		Case 4 (Heating Oil and Wind)		Case 5 (Diesel Oil and Wind)	
	Kong	Unal	Kong	Unal	Kong	Unal	Kong	Unal
$5.00	$0.15	$0.15	$0.21	$0.21	$0.08	$0.15	$0.19	$0.21
$5.50	$0.16	$0.16	$0.23	$0.23	$0.09	$0.16	$0.20	$0.23
$6.00	$0.17	$0.17	$0.25	$0.25	$0.10	$0.17	$0.21	$0.25
$6.50	$0.19	$0.19	$0.27	$0.27	$0.11	$0.19	$0.23	$0.27
$7.00	$0.20	$0.20	$0.29	$0.29	$0.11	$0.20	$0.24	$0.29
$7.50	$0.22	$0.22	$0.31	$0.31	$0.12	$0.22	$0.25	$0.31
$8.00	$0.23	$0.23	$0.33	$0.33	$0.13	$0.23	$0.27	$0.33
$8.50	$0.25	$0.25	$0.35	$0.35	$0.14	$0.25	$0.28	$0.35
$9.00	$0.26	$0.26	$0.38	$0.37	$0.15	$0.26	$0.29	$0.37
$9.50	$0.28	$0.28	$0.40	$0.39	$0.16	$0.28	$0.31	$0.39
$10.00	$0.29	$0.29	$0.42	$0.42	$0.16	$0.29	$0.32	$0.42
$10.50	$0.31	$0.31	$0.44	$0.44	$0.17	$0.30	$0.33	$0.44
$11.00	$0.32	$0.32	$0.46	$0.46	$0.18	$0.32	$0.35	$0.46
$11.50	$0.33	$0.33	$0.48	$0.48	$0.19	$0.33	$0.36	$0.48
$12.00	$0.35	$0.35	$0.50	$0.50	$0.20	$0.35	$0.37	$0.50
$12.50	$0.36	$0.36	$0.52	$0.52	$0.21	$0.36	$0.39	$0.52
$13.00	$0.38	$0.38	$0.54	$0.54	$0.21	$0.38	$0.40	$0.54
$13.50	$0.39	$0.39	$0.56	$0.56	$0.22	$0.39	$0.41	$0.56
$14.00	$0.41	$0.41	$0.58	$0.58	$0.23	$0.41	$0.43	$0.58
$14.50	$0.42	$0.42	$0.60	$0.60	$0.24	$0.42	$0.44	$0.60
$15.00	$0.44	$0.44	$0.63	$0.62	$0.25	$0.44	$0.45	$0.62
$15.50	$0.45	$0.45	$0.65	$0.64	$0.25	$0.45	$0.47	$0.64
$16.00	$0.47	$0.47	$0.67	$0.66	$0.26	$0.46	$0.48	$0.66
$16.50	$0.48	$0.48	$0.69	$0.68	$0.27	$0.48	$0.49	$0.68
$17.00	$0.49	$0.49	$0.71	$0.71	$0.28	$0.49	$0.51	$0.71
$17.50	$0.51	$0.51	$0.73	$0.73	$0.29	$0.51	$0.52	$0.73
$18.00	$0.52	$0.52	$0.75	$0.75	$0.30	$0.52	$0.53	$0.75
$18.50	$0.54	$0.54	$0.77	$0.77	$0.30	$0.54	$0.55	$0.77
$19.00	$0.55	$0.55	$0.79	$0.79	$0.31	$0.55	$0.56	$0.79
$19.50	$0.57	$0.57	$0.81	$0.81	$0.32	$0.57	$0.57	$0.81
$20.00	$0.58	$0.58	$0.83	$0.83	$0.33	$0.58	$0.59	$0.83
$20.50	$0.60	$0.60	$0.85	$0.85	$0.34	$0.60	$0.60	$0.85
$21.00	$0.61	$0.61	$0.88	$0.87	$0.34	$0.61	$0.61	$0.87

4.3 Results

4.3.1 Simple Payback Periods

Table 15 shows the simple payback periods of \$2000 and \$2500 Steffes systems in Kongiganak and Unalakleet at various costs of heating oil. They are calculated from Equation 2.22

$$Payback\ Period = \frac{Extra\ Investment}{Rate\ of\ Return} \tag{2.22}$$

where the rate of return is the rate of savings from the displaced fuel. The costs of \$2000 and \$2500 are used for the Steffes units because, in Fairbanks, the Cold Climate Housing Research Center (CCHRC) paid \$2400 for one similar unit [21]. It can be assumed that while it is more expensive to deliver the units to the remote villages, they would probably be eligible for a volume discount.

Table 15: Sensitivity Analysis for Payback Periods (in Years) for $2000 and $2500 Steffes Unit in Kongiganak and Unalakleet

Steffes Cost	**$2000**		**$2500**	
Diesel Cost	**Kongiganak**	**Unalakleet**	**Kongiganak**	**Unalakleet**
$4.00	3.93	10,121.46	4.92	12,651.82
$4.50	3.50	8,996.85	4.37	11,246.06
$5.00	3.15	8,097.17	3.93	10,121.46
$5.50	2.86	7,361.06	3.58	9,201.32
$6.00	2.62	6,747.64	3.28	8,434.55
$6.50	2.42	6,228.59	3.03	7,785.74
$7.00	2.25	5,783.69	2.81	7,229.61
$7.50	2.10	5,398.11	2.62	6,747.64
$8.00	1.97	5,060.73	2.46	6,325.91
$8.50	1.85	4,763.04	2.31	5,953.80
$9.00	1.75	4,498.43	2.19	5,623.03
$9.50	1.66	4,261.67	2.07	5,327.08
$10.00	1.57	4,048.58	1.97	5,060.73
$10.50	1.50	3,855.79	1.87	4,819.74
$11.00	1.43	3,680.53	1.79	4,600.66
$11.50	1.37	3,520.51	1.71	4,400.63
$12.00	1.31	3,373.82	1.64	4,217.27
$12.50	1.26	3,238.87	1.57	4,048.58
$13.00	1.21	3,114.29	1.51	3,892.87
$13.50	1.17	2,998.95	1.46	3,748.69
$14.00	1.12	2,891.84	1.40	3,614.81
$14.50	1.09	2,792.13	1.36	3,490.16
$15.00	1.05	2,699.06	1.31	3,373.82
$15.50	1.02	2,611.99	1.27	3,264.99
$16.00	0.98	2,530.36	1.23	3,162.96
$16.50	0.95	2,453.69	1.19	3,067.11
$17.00	0.93	2,381.52	1.16	2,976.90
$17.50	0.90	2,313.48	1.12	2,891.84
$18.00	0.87	2,249.21	1.09	2,811.52
$18.50	0.85	2,188.42	1.06	2,735.53
$19.00	0.83	2,130.83	1.04	2,663.54
$19.50	0.81	2,076.20	1.01	2,595.25
$20.00	0.79	2,024.29	0.98	2,530.36
$20.50	0.77	1,974.92	0.96	2,468.65
$21.00	0.75	1,927.90	0.94	2,409.87

Table 14 indicates that the Steffes unit is not economical in Unalakleet at any foreseeable cost of heating oil. However, the results show that installing a Steffes heater in every house in Kongiganak is a good decision at every realistic cost of oil, as the payback time is much lower than the expected lifespan of the project (20 years). The payback time is proportional to the reciprocal of the cost of oil ($/gal). Payback periods are longer in Unalakleet than they are in Kongiganak because Kongiganak has more excess electricity to be stored, and therefore, offsets a greater quantity of oil. In both villages, a more expensive unit has a longer payback time at every unit cost of oil because it needs to offset a greater quantity of oil to recover its initial cost. Because the rate of return (Equation 2.22) is inversely proportional to the unit cost of oil, the payback period versus heating oil cost curve for every scenario resembles a plot of $f(x)=1/x$. A plot of the payback periods for Kongiganak is given in Figure 84. This plot shows that at costs of oil greater than $1.00/gallon, using the Steffes to offset burning heating oil will offset its purchase cost. Further analysis is required to include additional factors, however.

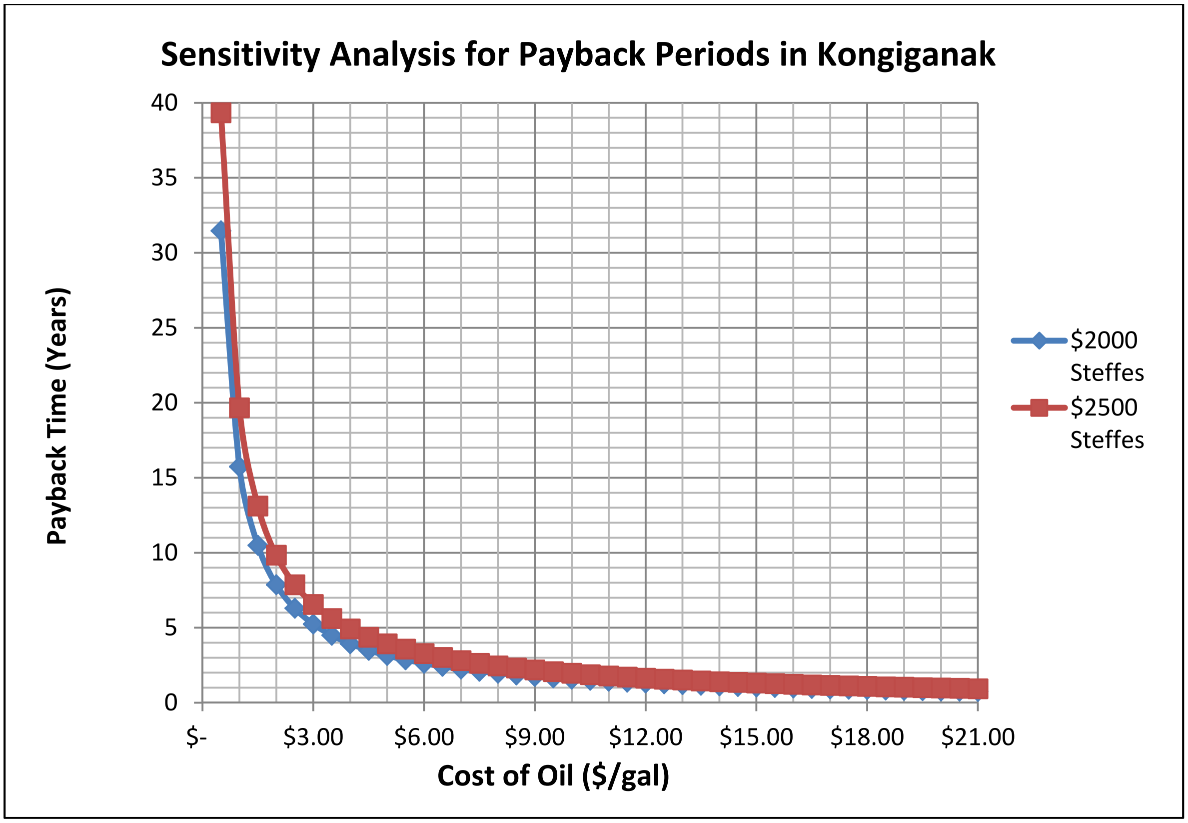

Figure 84: Simple Payback Times at Various Costs of Heating Oil in Kongiganak

The simple payback period for Unalakleet is given by Figure 85. In Unalakleet, the payback periods range from 1928 years for a $2000 Steffes unit when oil costs $21.00/gallon, to 101,215 years for a $2500 Steffes unit when oil costs $5.00/gallon. Obviously, these payback times are much too high to be practical for these costs of oil, Steffes unit, and electricity. Further analysis will be done for demonstration purposes.

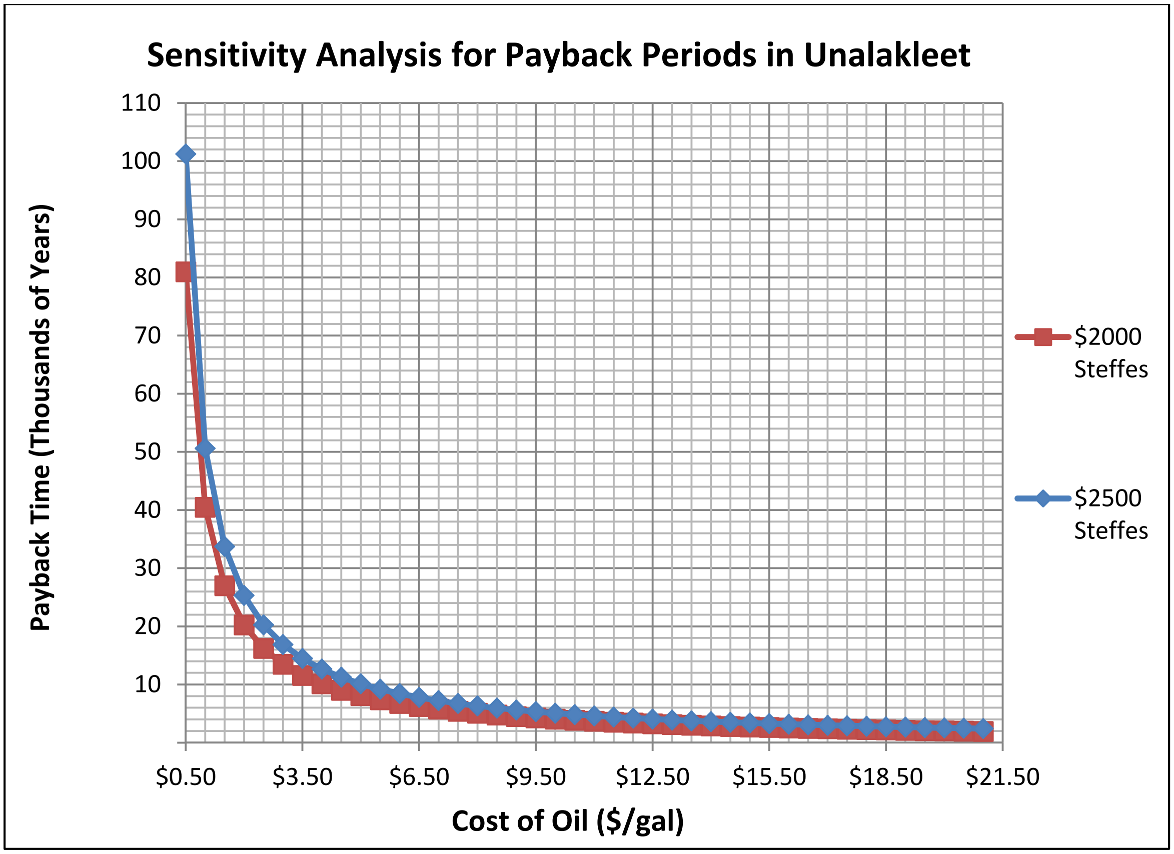

Figure 85: Simple Payback Times at Various Costs of Heating Oil in Unalakleet

The results of Figure 84 and Figure 85 must be further evaluated to account for the NPVs of the system over time with various investment rates.

4.4 Net Present Values

The NPV of the system, is calculated according to Equation 2.20.

$$P = \frac{A[1-(1+i)^{-n}]}{i} \tag{2.20}$$

The plots of NPVs versus the cost of heating oil of the upgraded systems (Toyo working with Steffes) are given by Figure 86. This figure indicates that, as the investment rate increases, the NPVs of both systems decrease. The higher the cost of oil, the more the NPV increases. A higher NPV means that a project offers a high value in the present, so any project with a positive NPV should be acted on [22].

In Kongiganak, the NPV of the Steffes ranges from $4423 at a 7% investment rate and low cost ($5.00/gallon) of fuel to $36,611 at a 3% investment rate and high cost ($21.00/gallon) of fuel. As the cost of fuel increases and the investment rate decreases, the NPV of the system increases linearly. The system is most economically beneficial at high costs of heating oil and lower rates of investment. However, its high NPV at all values shows that it is a good investment.

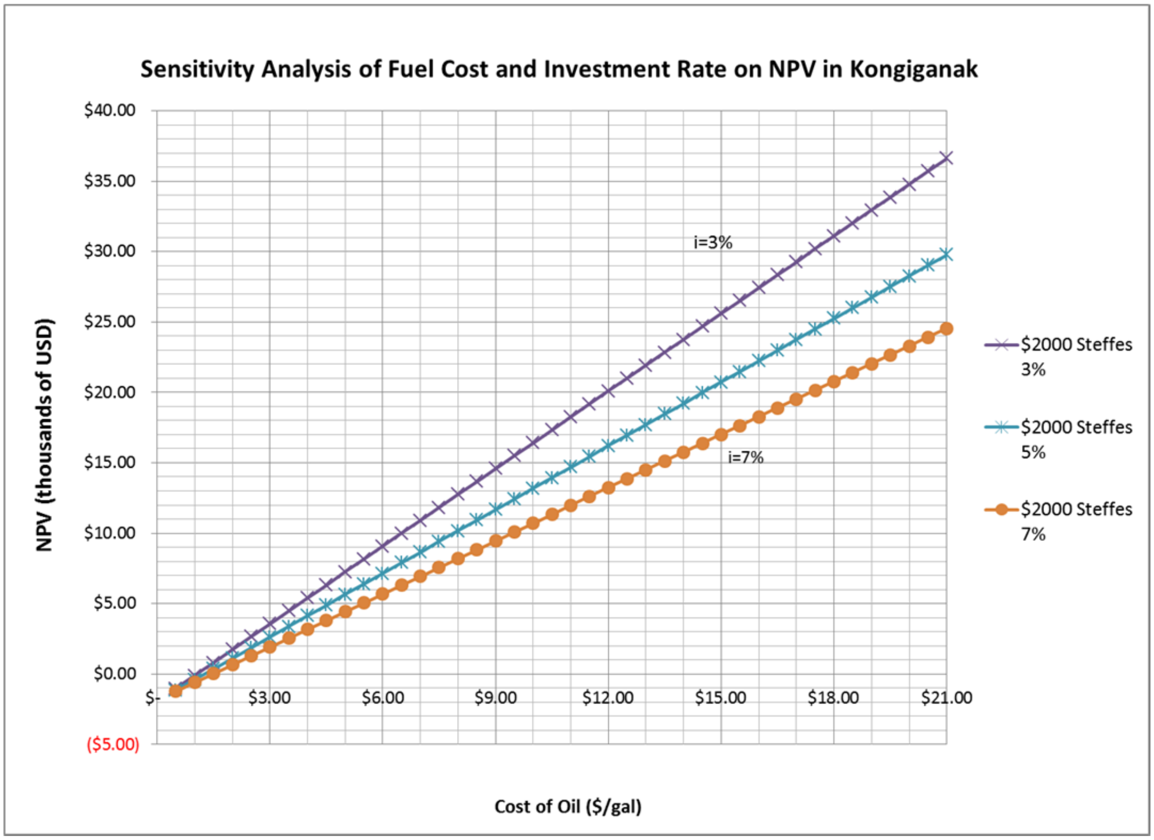

Figure 86: NPVs of a system of a Toyo working alone, and a Toyo working with a $2000 Steffes in Kongiganak

Figure 87 shows that the NPV at all costs of oil between $0.50/gallon and $21.00/gallon is negative and in the range of $\$10^4$. The cost of oil only offsets the initial cost of purchasing the Steffes unit at very high values.

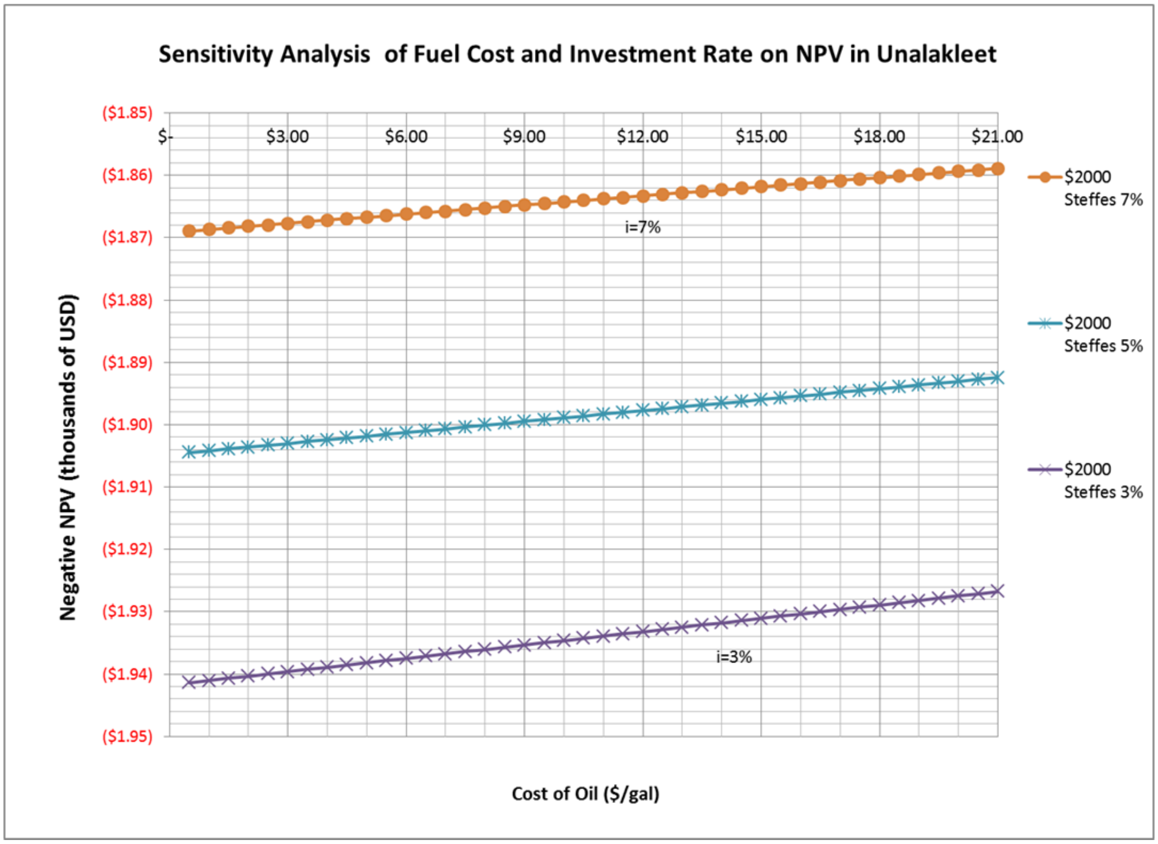

Figure 87: NPVs of a system of a Toyo working alone, and a Toyo working with a $2000 Steffes in Unalakleet

4.5 Evaluating the Results

In determining the best method to heat the houses, from a purely economic standpoint (ignoring human willingness to renovate the current system and the environmental advantages to reducing greenhouse gases), it is best to determine a cost of energy (COE) for the system in terms of the costs of improving the system, as well as in terms of the capital recovery factor (CRF). System improvements involve an investment in the present and result in future savings. However, when capital is borrowed, the value of money changes over the lifespan of the project. The CRF (Equation 2.21) accounts for this. The COE can be determined by Equation 4.1 from the cost of the Steffes (usually $2000), cost of fuel, and the A/P as described in Section 2.6.2 by Equation 2.21

$$COE = \frac{A}{P} C_{startup} + C_{fuel} \tag{4.1}$$

where $C_{startup}$ is the initial cost of purchase and installation, and C_{fuel} is the cost of fuel.

A/P was given by equation 2.19

$$CRF = \frac{A}{P} = \frac{i}{[1-(1+i)^{-n}]} \tag{2.19}$$

where 'A' is the annual sum of money, or the amount that is to be repaid annually to the lending entity and 'P' is the present worth. This is sometimes called the NPV. When the life of a Steffes unit is expected to be 20 years, the A/P values are given in Table 16.

Table 16: A/P Values at Various Investment Rates

	Investment Rate, *i* (%)		
	3%	**5%**	**7%**
A/P	0.067	0.080	0.094
Cost×(A/P), $2000	134.431	160.485	188.786
Cost×(A/P), $2500	168.039	200.607	235.982

Since the COE is dependent on the initial costs, A/P, and annual cost of fuel, it can be easy to use Table 16 to compare the relative importance of fuel and start-up costs. Table 16 shows the costs of fuel when the villages are heated with Toyo stoves burning heating oil.

Table 17: Maximum and Minimum Annual Costs of Fuel for Kongiganak and Unalakleet

	Kongiganak	**Unalakleet**
Annual Cost of Fuel @ $5.00/gal	$1,400	$1,540
Annual Cost of Fuel @ $21.00/gal	$4,060	$4,312

Comparing Tables 16 and 17 reveals that the cost of fuel is much higher than the cost of capital over a 20 year period for Kongiganak and Unalakleet, and there is much more variance in the maximum and minimum fuel prices than capital costs. Therefore, when the sensitivity analysis of fuel cost of COE of either community is analyzed, the cost of fuel has a greater impact on the COE than start-up cost.

4.5.1 Evaluating Kongiganak

The slope of the Toyo's COE is steeper than that of the Toyo-Steffes systems, and that they intersect at a relatively low cost of oil. This is shown graphically in Figure 88. The highlighted values of Table 18 are the crossover points. At costs of oil higher than these values, it is economical to install the Steffes heater to work with the Toyo stove. The amount of money saved increases at higher investment rates, and all scenarios become better as the unit cost of oil increases. Since the slope of the Toyo's COE is steeper than that of the Toyo-Steffes systems, they intersect at a relatively low cost of oil. Figure 88 gives a zoomed-in view of the crossover points.

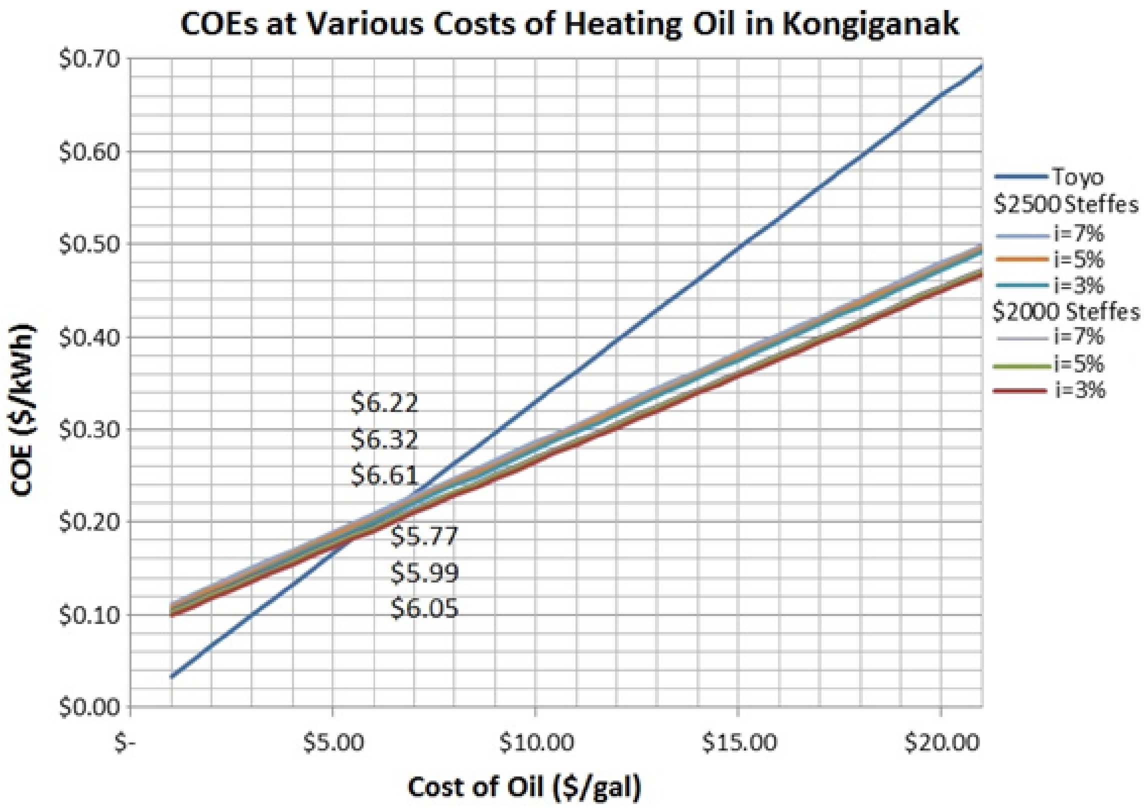

Figure 88: Comparing COEs for $2000 and $2500 Steffes Units at 3 Different Investment Rates (3%, 5%, and 7%) with That of the Toyo in Kongiganak

Table 18: Comparison of Energy Costs for Toyo With and Without Steffes at Various Fuel Prices and Investment Rates in Kongiganak

Cost of Oil ($/gal)		$2000 Steffes			$2500 Steffes		
	Toyo	3%	5%	7%	3%	5%	7%
$5.00	$0.1650	$0.1759	$0.1789	$0.1821	$0.1797	$0.1835	$0.1875
$5.50	$0.1815	$0.1854	$0.1884	$0.1916	$0.1893	$0.1930	$0.1970
$6.00	$0.1980	$0.1949	$0.1979	$0.2012	$0.1988	$0.2025	$0.2066
$6.50	$0.2145	$0.2044	$0.2074	$0.2107	$0.2083	$0.2120	$0.2161
$7.00	$0.2310	$0.2140	$0.2170	$0.2202	$0.2178	$0.2216	$0.2256
$7.50	$0.2475	$0.2235	$0.2265	$0.2297	$0.2273	$0.2311	$0.2351
$8.00	$0.2640	$0.2330	$0.2360	$0.2392	$0.2369	$0.2406	$0.2447
$8.50	$0.2805	$0.2425	$0.2455	$0.2488	$0.2464	$0.2501	$0.2542
$9.00	$0.2970	$0.2521	$0.2550	$0.2583	$0.2559	$0.2596	$0.2637
$9.50	$0.3135	$0.2616	$0.2646	$0.2678	$0.2654	$0.2692	$0.2732
$10.00	$ 0.3300	$0.2711	$0.2741	$0.2773	$0.2750	$0.2787	$0.2827
$10.50	$0.3465	$0.2806	$0.2836	$0.2869	$0.2845	$0.2882	$0.2923
$11.00	$0.3630	$0.2902	$0.2931	$0.2964	$0.2940	$0.2977	$0.3018
$11.50	$0.3795	$0.2997	$0.3027	$0.3059	$0.3035	$0.3073	$0.3113
$12.00	$0.3960	$0.3092	$0.3122	$0.3154	$0.3131	$0.3168	$0.3208
$12.50	$0.4125	$0.3187	$0.3217	$0.3250	$0.3226	$0.3263	$0.3304
$13.00	$0.4290	$0.3282	$0.3312	$0.3345	$0.3321	$0.3358	$0.3399
$13.50	$0.4456	$0.3378	$0.3408	$0.3440	$0.3416	$0.3454	$0.3494
$14.00	$0.4621	$0.3473	$0.3503	$0.3535	$0.3511	$0.3549	$0.3589
$14.50	$0.4786	$0.3568	$0.3598	$0.3630	$0.3607	$0.3644	$0.3685
$15.00	$0.4951	$0.3663	$0.3693	$0.3726	$0.3702	$0.3739	$0.3780
$15.50	$0.5116	$0.3759	$0.3788	$0.3821	$0.3797	$0.3834	$0.3875
$16.00	$0.5281	$0.3854	$0.3884	$0.3916	$0.3892	$0.3930	$0.3970
$16.50	$0.5446	$0.3949	$0.3979	$0.4011	$0.3988	$0.4025	$0.4065
$17.00	$0.5611	$0.4044	$0.4074	$0.4107	$0.4083	$0.4120	$0.4161
$17.50	$0.5776	$0.4140	$0.4169	$0.4202	$0.4178	$0.4215	$0.4256
$18.00	$0.5941	$0.4235	$0.4265	$0.4297	$0.4273	$0.4311	$0.4351
$18.50	$0.6106	$0.4330	$0.4360	$0.4392	$0.4369	$0.4406	$0.4446
$19.00	$0.6271	$0.4425	$0.4455	$0.4488	$0.4464	$0.4501	$0.4542
$19.50	$0.6436	$0.4520	$0.4550	$0.4583	$0.4559	$0.4596	$0.4637
$20.00	$0.6601	$0.4616	$0.4646	$0.4678	$0.4654	$0.4692	$0.4732
$20.50	$0.6766	$0.4711	$0.4741	$0.4773	$0.4749	$0.4787	$0.4827
$21.00	$0.6931	$0.4806	$0.4836	$0.4868	$0.4845	$0.4882	$0.4923

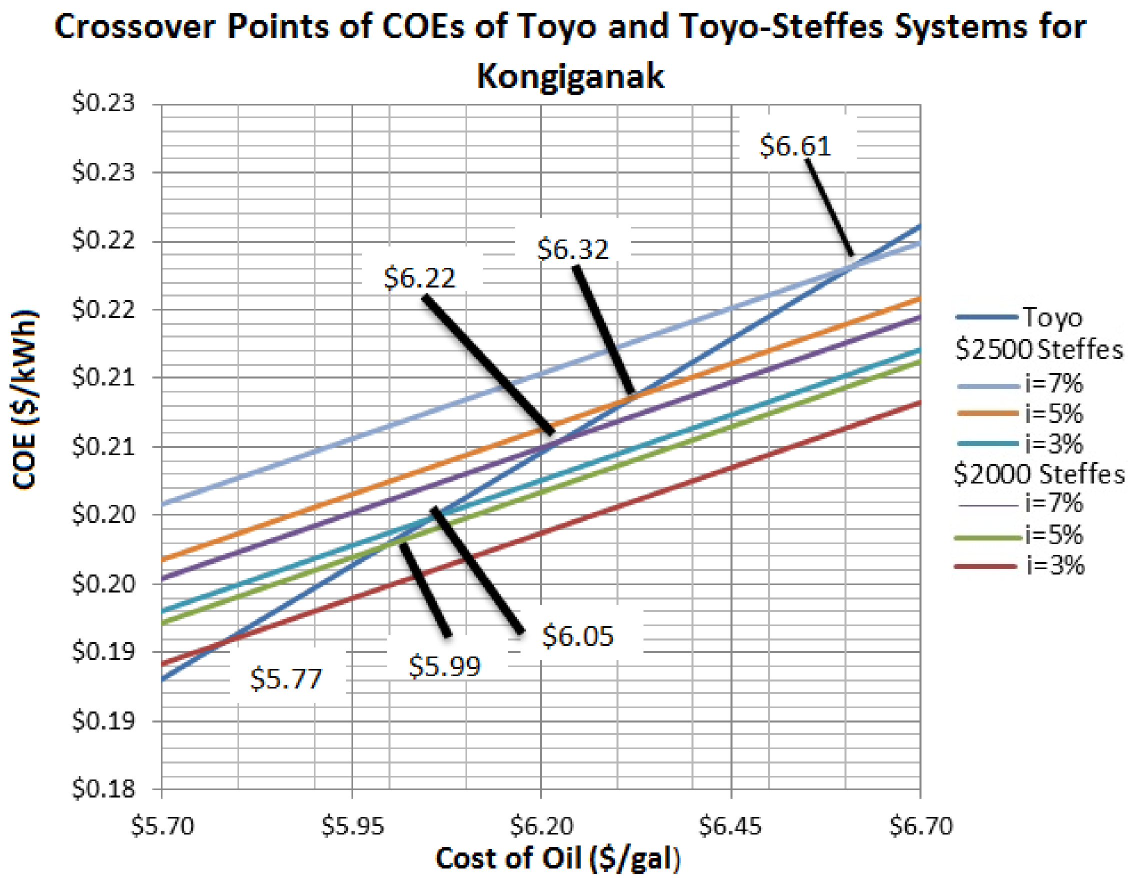

Figure 89: Comparing Crossover Points of COEs for $2000 and $2500 Steffes Units at 3 Different Investment Rates (3%, 5%, and 7%) with That of the Toyo in Kongiganak

4.5.2 Evaluating Unalakleet

Table 19 shows the crossover points for the COEs in Unalakleet. Because the wind energy displaces 0.05 gallons of heating oil, returns on the investment are not seen unless the cost of oil skyrockets to thousands of dollars per barrel.

Figure 90 shows the graph of the crossover points, which are nearly impossible to see because the effect of displacing 0.1155 MBTU is so negligible that the slope of the Toyo is less than 0.01% different from those of the adjusted COEs at the two initial costs and three investment rates.

Table 19: Crossover Points in Unalakleet

Cost of Oil ($/gal)		$2000 Steffes			$2500 Steffes		
	Toyo	3%	5%	7%	3%	5%	7%
$2,700.00	$90.0924	$90.0926	$90.0954	$90.0984	$90.0962	$90.0997	$90.1036
$2,800.00	$93.4292	$93.4288	$93.4316	$93.4347	$93.4324	$93.4360	$93.4398
$2,900.00	$96.7659	$96.7650	$96.7678	$96.7709	$96.7687	$96.7722	$96.7760
$3,000.00	$100.1027	$100.1012	$100.1040	$100.1071	$100.1049	$100.1084	$100.1122
$3,100.00	$103.4395	$103.4375	$103.4403	$103.4433	$103.4411	$103.4446	$103.4485
$3,200.00	$106.7762	$106.7737	$106.7765	$106.7795	$106.7773	$106.7809	$106.7847
$3,300.00	$110.1130	$110.1099	$110.1127	$110.1158	$110.1135	$110.1171	$110.1209
$3,400.00	$113.4497	$113.4461	$113.4489	$113.4520	$113.4498	$113.4533	$113.4571
$3,500.00	$116.7865	$116.7823	$116.7851	$116.7882	$116.7860	$116.7895	$116.7933
$3,600.00	$120.1232	$120.1186	$120.1214	$120.1244	$120.1222	$120.1257	$120.1296
$3,700.00	$123.4600	$123.4548	$123.4576	$123.4607	$123.4584	$123.4620	$123.4658
$3,800.00	$126.7968	$126.7910	$126.7938	$126.7969	$126.7947	$126.7982	$126.8020
$3,900.00	$130.1335	$130.1272	$130.1300	$130.1331	$130.1309	$130.1344	$130.1382
$4,000.00	$133.4703	$133.4635	$133.4663	$133.4693	$133.4671	$133.4706	$133.4745
$4,100.00	$136.8070	$136.7997	$136.8025	$136.8055	$136.8033	$136.8068	$136.8107
$4,200.00	$140.1438	$140.1359	$140.1387	$140.1418	$140.1395	$140.1431	$140.1469
$4,300.00	$143.4805	$143.4721	$143.4749	$143.4780	$143.4758	$143.4793	$143.4831
$4,400.00	$146.8173	$146.8083	$146.8111	$146.8142	$146.8120	$146.8155	$146.8193
$4,500.00	$150.1541	$150.1446	$150.1474	$150.1504	$150.1482	$150.1517	$150.1556
$4,600.00	$153.4908	$153.4808	$153.4836	$153.4867	$153.4844	$153.4880	$153.4918
$4,700.00	$156.8276	$156.8170	$156.8198	$156.8229	$156.8207	$156.8242	$156.8280
$4,800.00	$160.1643	$160.1532	$160.1560	$160.1591	$160.1569	$160.1604	$160.1642

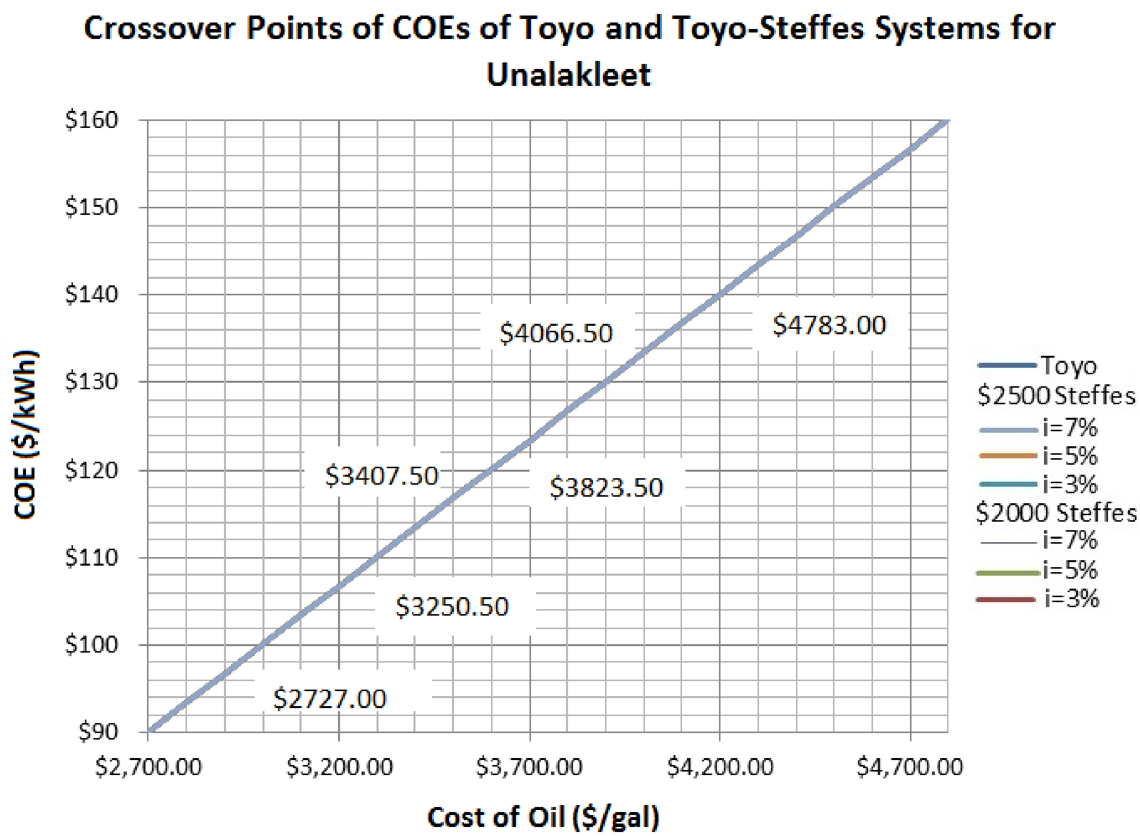

Figure 90: Comparing COEs for $2000 and $2500 Steffes Units at Three Different Investment Rates (3%, 5%, and 7%) with That of the Toyo in Unalakleet

The crossover points for Kongiganak, as shown in Table 20, occur at costs of oil of $5.77/gallon for a $2000 Steffes and 3% investment rate to $6.61/gallon for a $2500 Steffes and a 7% investment rate, as shown. At these costs of oil, the costs of energy are lower for the Toyo than for the Toyo working with the Steffes. Above these values, the Steffes becomes a better value. Since the average cost of oil, $7.10/gallon, is higher than all values of crossover points, the price of heating oil is expected to stay above the point where the Toyo is better than the Toyo-Steffes system.

Table 20: Crossover Points for Unalakleet and Kongiganak

		$2000			$2500		
		3%	5%	5%	3%	5%	5%
Kong	Heating Oil Cost ($/gal)	$5.77	$5.99	$6.22	$6.05	$6.32	$6.61
	COE ($/kWh)	$0.19	$0.20	$0.21	$0.20	$0.21	$0.22
Unal	Heating Oil Cost ($/gal)	$2727.00	$3250.50	$3823.50	$3407.50	$4066.50	$4783.00
	COE ($/kWh)	$90.90	$108.46	$127.58	$113.70	$135.68	$159.60

The crossover points for Unlakleet range from $2727 to $4783, which are several hundred times the crossover points for Kongiganak and the average price of oil. It is unreasonable to consider installing the Steffes units in Unalakleet at this time, but further analysis of Kongiganak will be further illustrate the infeasibility of this system in Unalakleet.

4.5.3 Re-evaluating the Results with Infrastructure Changes

The previous results are based on the capital cost of the heaters. This does not include any required electrical infrastructure upgrades such as new wiring and circuit breakers to handle the power demand from the electrothermal heaters. Further analysis is needed to take into account the electrical infrastructure upgrades required to connect the electrothermal heaters to the power grid in the communities. These upgrades include installation of a 2/0 insulated conductor to each house in order to handle the electric power demanded by the heaters.

The area of Kongiganak is 1.9 $miles^2$ [4], and Unalakleet's is 5.2 $miles^2$ [6], with the houses grouped in a tight cluster. It has been assumed that each house uses 200-250 feet of conductor. Standard costs for 2/0 insulated conductor are $10,000/500 feet of conductor, so each house requires an average of $2,000-$2500 worth of conductor [20]. Re-calculated economic analysis based on total costs of $4,000 and $5,000 for Kongiganak are shown in Table 20, where the crossover points are highlighted, and shown graphically in Figure 91.

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Table 21: Crossover points in Kongiganak when Infrastructure Changes Are Taken Into Account

		$4000			$5000		
	Toyo	3%	5%	7%	3%	5%	7%
$6.85	$0.23	$0.23	$0.23	$0.24	$0.23	$0.24	$0.25
$6.86	$0.23	$0.23	$0.23	$0.24	$0.23	$0.24	$0.25
$6.87	$0.23	$0.23	$0.23	$0.24	$0.23	$0.24	$0.25
$6.88	$0.23	$0.23	$0.23	$0.24	$0.23	$0.24	$0.25
$6.89	$0.23	$0.23	$0.23	$0.24	$0.23	$0.24	$0.25
$6.90	$0.23	$0.23	$0.23	$0.24	$0.24	$0.24	$0.25
$7.29	$0.24	$0.23	$0.24	$0.25	$0.24	$0.25	$0.26
$7.30	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.31	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.32	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.33	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.34	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.35	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.36	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.37	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.38	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.39	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.40	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.41	$0.24	$0.24	$0.24	$0.25	$0.24	$0.25	$0.26
$7.42	$0.24	$0.24	$0.24	$0.25	$0.25	$0.25	$0.26
$7.43	$0.25	$0.24	$0.24	$0.25	$0.25	$0.25	$0.26
$7.44	$0.25	$0.24	$0.24	$0.25	$0.25	$0.25	$0.26
$7.75	$0.25	$0.24	$0.24	$0.25	$0.25	$0.25	$0.26
$7.76	$0.25	$0.24	$0.24	$0.25	$0.25	$0.25	$0.26
$7.77	$0.25	$0.24	$0.25	$0.25	$0.25	$0.25	$0.26
$7.78	$0.25	$0.24	$0.25	$0.25	$0.25	$0.25	$0.26
$7.79	$0.25	$0.24	$0.25	$0.25	$0.25	$0.25	$0.26
$7.94	$0.26	$0.24	$0.25	$0.25	$0.25	$0.26	$0.27
$7.95	$0.26	$0.24	$0.25	$0.25	$0.25	$0.26	$0.27
$7.96	$0.26	$0.24	$0.25	$0.26	$0.25	$0.26	$0.27
$7.97	$0.26	$0.24	$0.25	$0.26	$0.25	$0.26	$0.27
$7.98	$0.26	$0.24	$0.25	$0.26	$0.25	$0.26	$0.27
$8.52	$0.28	$0.25	$0.26	$0.27	$0.26	$0.27	$0.28
$8.53	$0.28	$0.25	$0.26	$0.27	$0.26	$0.27	$0.28
$8.54	$0.28	$0.25	$0.26	$0.27	$0.26	$0.27	$0.28
$8.55	$0.28	$0.25	$0.26	$0.27	$0.26	$0.27	$0.28
$8.56	$0.28	$0.25	$0.26	$0.27	$0.26	$0.27	$0.28

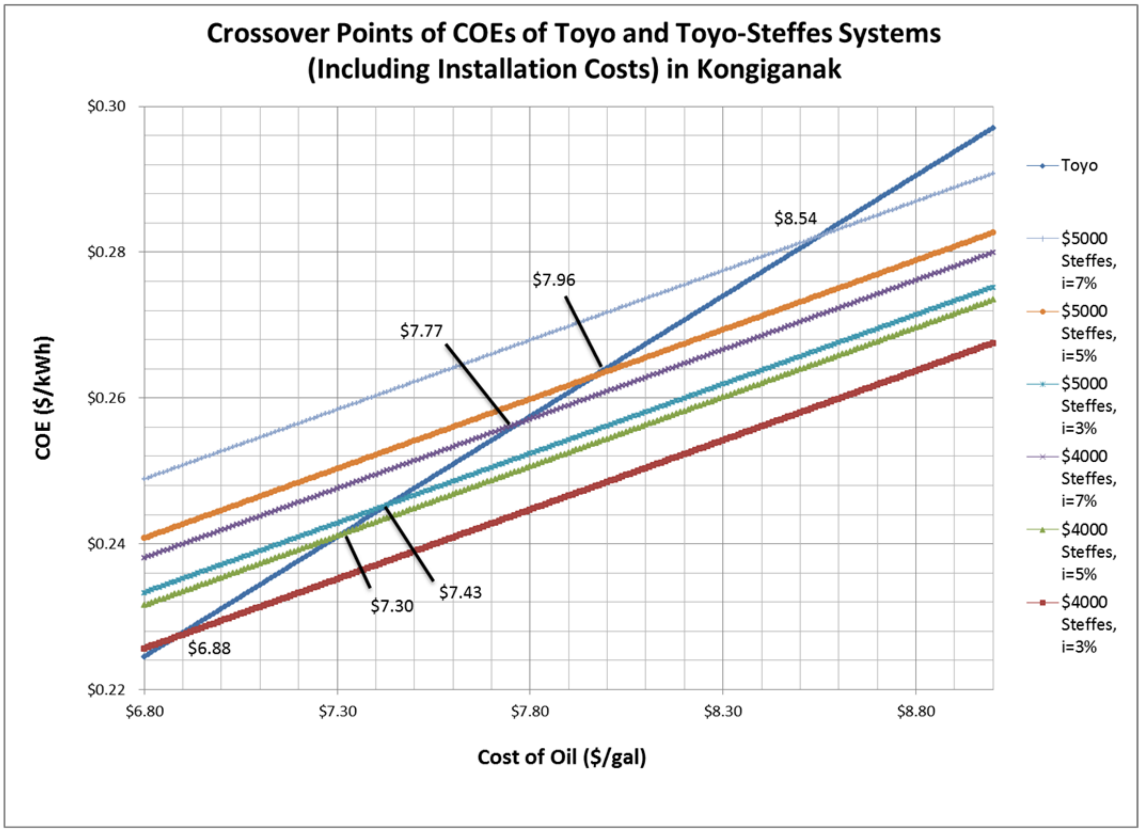

Figure 91: Crossover Points of COEs of Toyo and Toyo-Steffes Systems (Including Installation Costs (in Kongiganak) for a $4000 and $5000 System)

Every crossover point in Table 21, except for a $4000 Steffes with a 3% investment rate is above Kongiganak's average cost of oil of $7.10/gallon. Consequently, when these infrastructure changes are factored in, it no longer is advantageous to install the Steffes unit and its entire surrounding infrastructure.

As expected, adding the cost of installation makes Unalakleet even less feasible. The crossover points are shown in Table 22. The changes of COE with respect to cost of oil are very small.

Table 22: Crossover points in Unalakleet when Infrastructure Changes Are Taken Into Account

		$4000			$5000		
	Toyo	3%	5%	7%	3%	5%	7%
$5,400.00	$180.18	$180.19	$180.19	$180.20	$180.19	$180.20	$180.21
$5,450.00	$181.85	$181.85	$181.86	$181.87	$181.86	$181.87	$181.88
$5,500.00	$183.52	$183.52	$183.53	$183.53	$183.53	$183.54	$183.54
$5,550.00	$185.19	$185.19	$185.20	$185.20	$185.20	$185.20	$185.21
$5,600.00	$186.86	$186.86	$186.86	$186.87	$186.86	$186.87	$186.88
$6,400.00	$213.55	$213.55	$213.55	$213.56	$213.55	$213.56	$213.57
$6,450.00	$215.22	$215.22	$215.22	$215.23	$215.22	$215.23	$215.25
$6,500.00	$216.89	$216.88	$216.89	$216.90	$216.89	$216.90	$216.91
$6,550.00	$218.56	$218.55	$218.56	$218.56	$218.56	$218.57	$218.57
$6,600.00	$220.23	$220.22	$220.23	$220.23	$220.23	$220.23	$220.24
$6,650.00	$221.89	$221.89	$221.89	$221.90	$221.90	$221.90	$221.91
$6,700.00	$223.56	$223.56	$223.56	$223.57	$223.56	$223.57	$223.58
$6,750.00	$225.23	$225.22	$225.23	$225.24	$225.23	$225.24	$225.25
$6,800.00	$226.90	$226.89	$226.90	$226.90	$226.90	$226.91	$226.91
$6,850.00	$228.57	$228.56	$228.57	$228.57	$228.57	$228.57	$228.58
$6,900.00	$230.24	$230.23	$230.23	$230.24	$230.24	$230.24	$230.25
$6,950.00	$231.90	$231.90	$231.90	$231.91	$231.90	$231.91	$231.92
$7,600.00	$253.59	$253.58	$253.59	$253.59	$253.59	$253.60	$253.60
$7,650.00	$255.26	$255.25	$255.26	$255.26	$255.26	$255.26	$255.27
$7,700.00	$256.93	$256.92	$256.92	$256.93	$256.93	$256.93	$256.94
$7,750.00	$258.60	$258.59	$258.59	$258.60	$258.59	$258.60	$258.61
$7,800.00	$260.27	$260.25	$260.26	$260.27	$260.26	$260.27	$260.28
$7,850.00	$261.94	$261.92	$261.93	$261.93	$261.93	$261.94	$261.94
$7,900.00	$263.60	$263.59	$263.60	$263.60	$263.60	$263.61	$263.61
$7,950.00	$265.27	$265.26	$265.26	$265.27	$265.27	$265.27	$265.28
$8,000.00	$266.94	$266.93	$266.93	$266.94	$266.93	$266.94	$266.95
$8,050.00	$268.61	$268.60	$268.60	$268.61	$268.60	$268.61	$268.62
$8,100.00	$270.28	$270.26	$270.27	$270.27	$270.27	$270.28	$270.29
$8,150.00	$271.95	$271.93	$271.94	$271.94	$271.94	$271.95	$271.95
$8,200.00	$273.61	$273.60	$273.60	$273.61	$273.61	$273.61	$273.62
$9,450.00	$315.32	$315.30	$315.31	$315.31	$315.31	$315.32	$315.32
$9,500.00	$316.99	$316.97	$316.98	$316.98	$316.98	$316.98	$316.99
$9,550.00	$318.66	$318.64	$318.64	$318.65	$318.65	$318.65	$318.66

As the crossover points for installing a system in Unalakleet occur where the cost of oil is thousands of dollars, it is not viable to install the Steffes units in Unalakleet. Further research would be necessary to determine whether it is viable to install additional turbines to harness wind energy for domestic heating.

The first model that did not account for the installation costs confirmed that it was advantageous to install Steffes units at most oil prices. When all other factors are held constant, installing the Steffes unit resulted in a lower COE for every scenario tested. In Kongiganak, when oil prices were around $21.00, installing the Steffes lowered the COE by 25%. In Unalakleet, when heating oil was $5.00/gallon, there was negligible savings. From these findings, it has been determined that the best communities for the Steffes heaters to be installed have as many as the following characteristics as possible:

1. A lot of unused excess wind energy
2. Few residences that require energy
3. High heating oil prices
4. High diesel oil prices

Of these four traits, high heating oil prices are the biggest indicator of a good candidate as the slopes are very sensitive for a change in fuel cost, followed closely by a lot of excess wind energy. A village with many residences can take advantage of wind energy by diverting heat to community buildings. Most Alaskan villages do not use diesel fuel to heat, but if any have existing electric heaters, powering those with excess wind energy would be a good solution.

Chapter 5: Summary, Conclusions and Future Research

5.1 Summary

It was useful to model electrothermal masonry heating and storage devices to analyze the economics of using excess electricity from wind generation to heat buildings in Alaskan villages. Different methods of heating buildings in these communities which rely primarily on Toyo oil stoves were analyzed to see at what prices of heating oil and diesel oil the electrothermal masonry systems are economically viable. For situations where wind energy displaces oil consumption, it becomes advantageous to displace oil at every unit price of oil above a certain point. This crossover point was useful for determining the economic viability of a project. If the crossover point was much higher than the projected cost of oil, the project was not economically advantageous.

5.1.1 Kongiganak Summary

Of the two communities, Kongiganak was expected to be a better candidate. Its average temperature is higher than that of Unalakleet, its windspeed is slightly greater, and the ratio of wind turbines to homes was greater. It was shown that, when accounting for just the purchase cost, the Steffes was economically beneficial in Kongiganak at heating oil costs above $5.50/gallon for a $2000 unit and a 3% investment rate, and $6.50/gallon at a $2500 unit and a 7% investment rate. When accounting for the cost of installing new electrical wiring to support the higher electricity flows, the total cost increased to $4000 and $5000. The crossover points are at $6.88/gallon for a $4000 unit and a 3% investment rate, and $8.54/gallon for a $5000 unit and a 7% investment rate. These values indicate that installing the Steffes units is beneficial if the cost of the Steffes and the investment rate is low, or oil prices are expected to rise.

5.1.2 Unalakleet Summary

In Unalakleet, the crossover points are at $2727.00/gallon for a $2000 unit at a 3% investment rate, and $4783.00/gallon for a $2500 unit at a 7% investment rate. For a $4000 costs including the new electrical wiring, with a 3% investment rate, the crossover point is at the astronomical cost of fuel of $5450/gallon, and for a $5000 unit and bus cable at a 7% investment rate, the crossover point is at $9500/gallon.

5.2 Effect of Efficiencies on Results

Changing the efficiency of the wind generators decreases the annual costs of heating and the unit costs of energy. Table 23 shows the annual costs of heating and COEs for case 4 in Kongiganak at four different wind turbine efficiencies. The actual efficiency of Kongiganak's turbines, 25%, is highlighted.

Table 23: Annual costs and COEs of Case 4 for Kongiganak at Various Wind Turbine Efficiencies

	20%	25%	30%	35%		20%	25%	30%	35%
	Annual Cost					**COE**			
$5.00	$1,471.18	$1,433.95	$1,420.07	$1,413.73		$0.16	$0.16	$0.16	$0.16
$5.50	$1,564.51	$1,517.05	$1,492.86	$1,478.48		$0.17	$0.17	$0.17	$0.17
$6.00	$1,657.83	$1,600.15	$1,565.65	$1,543.23		$0.18	$0.18	$0.18	$0.17
$6.50	$1,751.15	$1,683.25	$1,638.44	$1,607.98		$0.19	$0.19	$0.18	$0.18
$7.00	$1,844.48	$1,766.35	$1,711.23	$1,672.73		$0.20	$0.20	$0.19	$0.19
$7.50	$1,937.80	$1,849.45	$1,784.02	$1,737.48		$0.21	$0.21	$0.20	$0.19
$8.00	$2,031.12	$1,932.55	$1,856.81	$1,802.23		$0.22	$0.22	$0.21	$0.20
$8.50	$2,124.45	$2,015.65	$1,929.60	$1,866.98		$0.23	$0.23	$0.22	$0.21
$9.00	$2,217.77	$2,098.75	$2,002.39	$1,931.74		$0.24	$0.24	$0.22	$0.22
$9.50	$2,311.09	$2,181.85	$2,075.18	$1,996.49		$0.25	$0.25	$0.23	$0.22
$10.00	$2,404.42	$2,264.95	$2,147.97	$2,061.24		$0.26	$0.26	$0.24	$0.23
$10.50	$2,497.74	$2,348.05	$2,220.76	$2,125.99		$0.27	$0.26	$0.25	$0.24
$11.00	$2,591.06	$2,431.15	$2,293.55	$2,190.74		$0.28	$0.27	$0.26	$0.24
$11.50	$2,684.39	$2,514.25	$2,366.34	$2,255.49		$0.29	$0.28	$0.26	$0.25
$12.00	$2,777.71	$2,597.35	$2,439.13	$2,320.24		$0.30	$0.29	$0.27	$0.26
$12.50	$2,871.03	$2,680.45	$2,511.92	$2,384.99		$0.31	$0.30	$0.28	$0.27
$13.00	$2,964.36	$2,763.55	$2,584.71	$2,449.74		$0.32	$0.31	$0.29	$0.27
$13.50	$3,057.68	$2,846.65	$2,657.50	$2,514.49		$0.34	$0.32	$0.30	$0.28
$14.00	$3,151.00	$2,929.75	$2,730.29	$2,579.24		$0.35	$0.33	$0.31	$0.29
$14.50	$3,244.33	$3,012.85	$2,803.08	$2,643.99		$0.36	$0.34	$0.31	$0.30
$15.00	$3,337.65	$3,095.95	$2,875.87	$2,708.74		$0.37	$0.35	$0.32	$0.30
$15.50	$3,430.98	$3,179.05	$2,948.66	$2,773.49		$0.38	$0.36	$0.33	$0.31
$16.00	$3,524.30	$3,262.15	$3,021.45	$2,838.24		$0.39	$0.37	$0.34	$0.32
$16.50	$3,617.62	$3,345.25	$3,094.24	$2,902.99		$0.40	$0.38	$0.35	$0.32
$17.00	$3,710.95	$3,428.35	$3,167.03	$2,967.75		$0.41	$0.39	$0.35	$0.33
$17.50	$3,804.27	$3,511.45	$3,239.82	$3,032.50		$0.42	$0.40	$0.36	$0.34
$18.00	$3,897.59	$3,594.55	$3,312.61	$3,097.25		$0.43	$0.40	$0.37	$0.35
$18.50	$3,990.92	$3,677.65	$3,385.40	$3,162.00		$0.44	$0.41	$0.38	$0.35
$19.00	$4,084.24	$3,760.75	$3,458.19	$3,226.75		$0.45	$0.42	$0.39	$0.36
$19.50	$4,177.56	$3,843.85	$3,530.98	$3,291.50		$0.46	$0.43	$0.40	$0.37
$20.00	$4,270.89	$3,926.95	$3,603.77	$3,356.25		$0.47	$0.44	$0.40	$0.37
$20.50	$4,364.21	$4,010.05	$3,676.56	$3,421.00		$0.48	$0.45	$0.41	$0.38
$21.00	$4,457.53	$4,093.15	$3,749.35	$3,485.75		$0.49	$0.46	$0.42	$0.39

These values indicate that COEs are improved dramatically at higher costs of oil. When heating oil is $5.00/gallon, there is no difference in the COE. At $21.00 a gallon, every 5% increase in efficiency results in a savings of $0.03-$0.04/kWh, or a 6%-7% improvement as shown in Figure 92. Increasing the efficiency of the system decreases the COE and reduces the savings that could then be realized by using the Steffes. This is to say, further analysis is needed, but any improvement made should probably have lower initial costs than the purchase and installation of the Steffes unit, in order for the system to benefit.

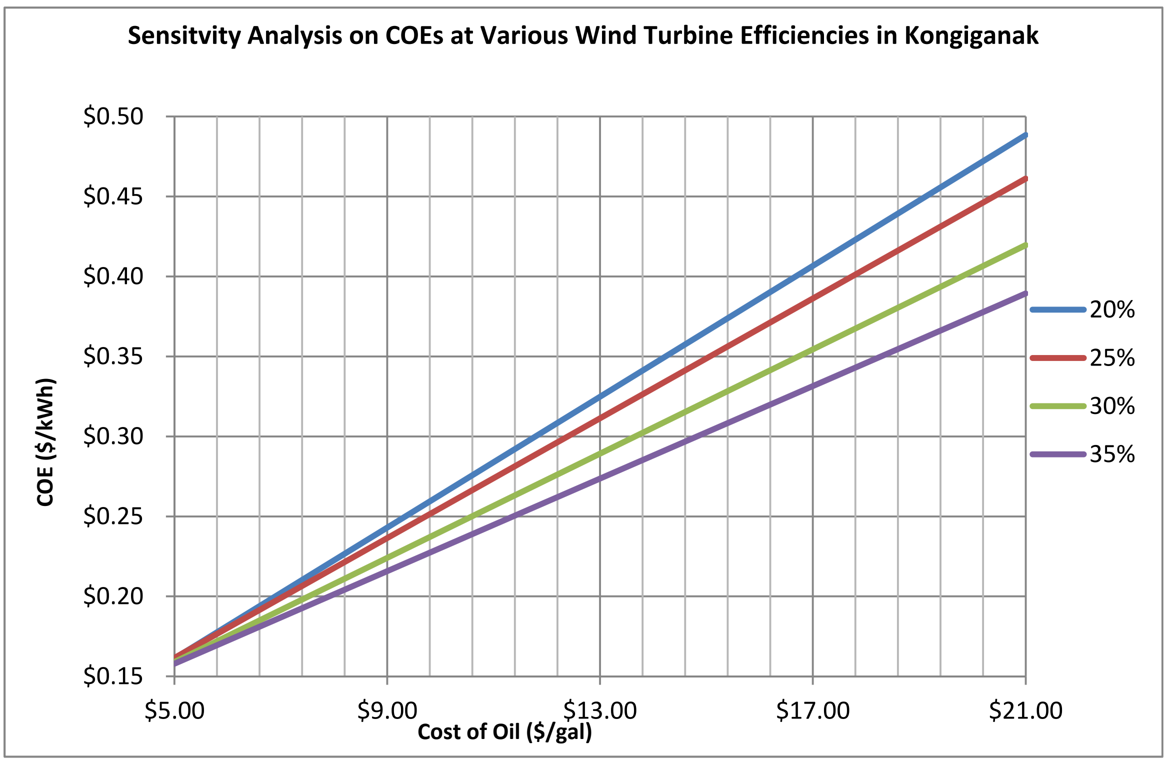

Figure 92: Sensitivity Analysis of the Effect of Efficiency on Costs of Energy in Kongiganak

5.3 Effect of Changing R-values on House Heating

Increasing the R-value of the house will improve the overall system efficiency by reducing the BTU of energy needed to heat the house. However, the net present value is related to the amount of heating oil displaced. To break even during the simple payback period, the Steffes system must offset a minimum of $200-$250/year for 20 years. At $5.00/gallon, this means offsetting 40-50 gallons of heating oil (4.05-5.06MBTU). At $21.00/gallon, 9.5-12 gallons of heating oil must be offset (1-1.2 MBTU).

In Kongiganak, a small house with R-20 insulation harnesses 12.95 MBTU to make up its heating load of 28.49 MBTU, most of which is harnessed during the winter. A quick modification of the 'small house in Kongiganak' model revealed that houses with R-values ranging from R-15 to R-70 require 8.9-38.85 MBTU to heat, as shown in Table 24. For greater R-values, less energy is required and a greater proportion of the energy can be harnessed from the wind. However, at a high enough R-value, the Steffes harnesses the maximum available energy and offsets less than enough energy to break even, i.e.: it is preferable to meet the low heating needs with heating oil. This comes at an R-value higher than R-70, which is higher than most houses in arctic climate zones (AHFC does not recommend anything over R-65) [51]. At any reasonable and foreseeable R-value, the Steffes still offsets enough energy to be viable at heating oil costs above the crossover points from Table 20 in section 4.5.3, ranging from $6.88/gallon to $8.54/gallon.

In Unalakleet, the wind turbines cannot harness enough excess electricity to be viable, so insulation levels are irrelevant.

Table 24: Energy Required to Heat Small Houses in Kongiganak at Various R-Values

Insulation	R-15	R-20	R-30	R-40	R-50	R-60	R-70
Heat Required (MBTU) In Kongiganak	38.85	28.49	20.07	15.04	12.31	10.27	8.9

5.4 Model Improvements

The model of the house could be improved. Since the air inside the house was modeled as one homogenous mass, the energy required to heat the house is under-estimated. A more accurate model would include a low-temperature boundary layer of air at the inner wall of each building. House components such as furniture and appliances also have different thermal masses and heat capacities which can hold and transfer heat energy differently from still air. A better model would also include the thermal masses in the house that are large enough to store a significant quantity of heat energy. Additionally, wind and the still air layer outside the house were not modeled. Unless the wind is constantly blowing, and there are no other buildings to break up the wind at the walls of the house, there is a small boundary layer of still air that insulates the house slightly. Taking this into account would reduce the amount of energy the model predicts is required to heat the house.

5.5 Future Research

The primary goal of this project was to create a model of an electrothermal masonry heater and storage unit that uses excess wind resources for heating and storage, as well as models of the existing buildings, and the electric and thermal demands of the residents. This model was successfully applied to two distinctly different communities. Further modifications to the model would make it more modular: that is to say, it should have some sort of choosing mechanism so that a computer algorithm could prioritize whether a town should install one small Steffes unit in each residence, or install fewer of them in the larger buildings.

The next step in this project is to include other factors in the selection of the ideal heating system. For example, it could be useful to include a feature that would allow the user to more easily apply the different types of groups of buildings (small houses, big buildings, community centers) as loads to gauge more easily whether it is better to install a few heating units in larger buildings or many heating units in smaller buildings. It could also be useful to create a simulation that includes a map of the community to show which buildings are closest to the turbines and therefore require less 2/0 conductor in order to install a Steffes unit.

More research can be done with hot water heaters to include them more easily into the models. An on/off switch can be employed to run each simulation with an optional water heater attached as a secondary dump load, as there were many instances during summer months when there was excess electricity and the Steffes heaters were fully charged. During summer, even when domestic heat is not demanded, hot water is needed for showering and cleaning.

All things considered, an organized and highly customizable model based on this model would benefit Alaska, which according to the US Census, has 355 locations with a variety of populations, climates, and prices of oil [23]. As new technologies become viable at different prices, and as the price of oil changes, technologies should be reassessed regularly. The ultimate goal is to provide Alaskans with economically sound and environmentally friendly methods of meeting their domestic heating and electric needs. This project can potentially make infrastructure improvement assessments easier.

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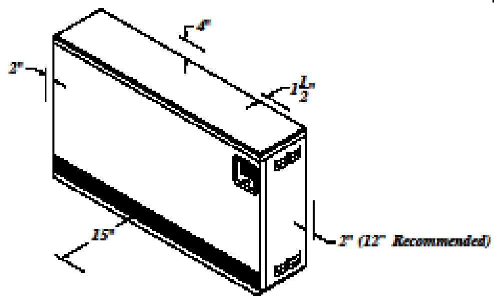
Appendix A: Steffes Models 2102-2106 Technical Data Sheets

Technical Data Sheet
Room Heating Unit
Electric Thermal Storage Heating System
Models: 2102, 2103, 2104, 2105, 2106

5-Year Limited Manufacturer's Warranty

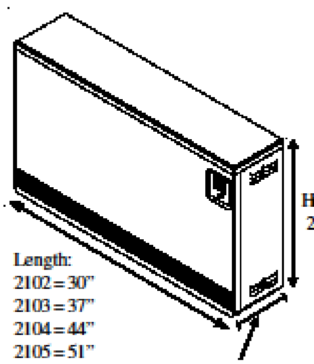
STEFFES CORPORATION

Placement and Clearances



- All heater surfaces must be kept 4" minimum from combustible material.
- A minimum of 12" clearance is recommended on the right side of heater to ensure accurate room temperature sensing and for servicing purposes. If less than 12" is available, an optional remote room temperature sensor is recommended.
- Heater may be recessed into a wall but do not enclose or obstruct access to heaters front panel and grill.
- Weight of heater must be considered when selecting placement location. Refer to specification chart for heater weights.
- Generally, the heater can be placed on any standard flooring. Depending on temperature threshold of floor covering or carpet thickness, it may be necessary to elevate unit off the floor.
- Room heating units are not recommended for applications where petroleum or chemical based contaminates such as paints, varnishes or other combustibles are present in the air. Odors such as these may be amplified. Special requirements must be considered if placing heater in a garage or other area where combustible vapors may be present.
- Avoid installing heater near an open stairwell or near external sources of heat or cold.
- Consult national, state and local building code requirements for electrical appliance to ensure proper installation.

Unit Dimensions



Field Connection and Circuit Breaker Sizing Reference Chart

NOTE **This chart reflects only the code interpretation of Steffes. It is the responsibility of the installer to comply with all applicable codes and regulations.**

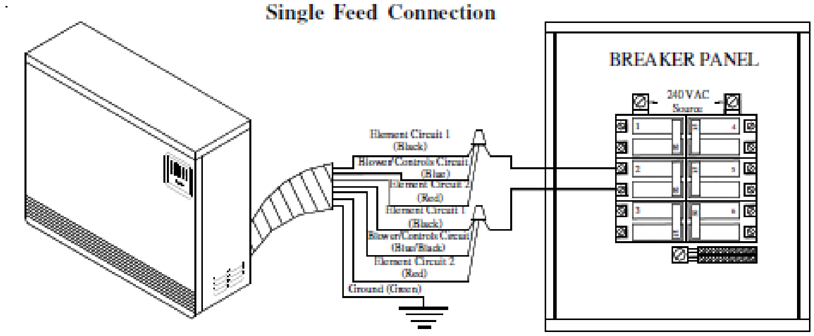
	MAXIMUM kW			
Wire Size	**240VAC**	**277VAC**	**208VAC**	**Maximum Circuit Breaker Size**
#14 AWG	2.8	3.3	2.4	15
#12 AWG	3.8	4.4	3.3	20
#10 AWG	5.7	6.6	4.9	30
#8 AWG	7.6	8.8	6.6	40
#6 AWG	11.5	13.2	9.9	60

Use copper wire rated at 75°C minimum only.

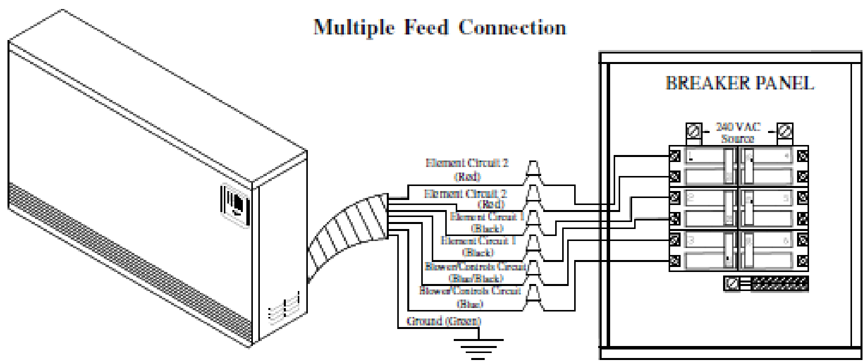
Line Voltage Connections

All 2100 series room heating units are factory configured for single or two circuit element feed connections. The fan/controls circuit can be powered from the element circuit or from a separate feed. (The heater must be wired in compliance with all applicable codes and regulations.)

Single Feed Connection



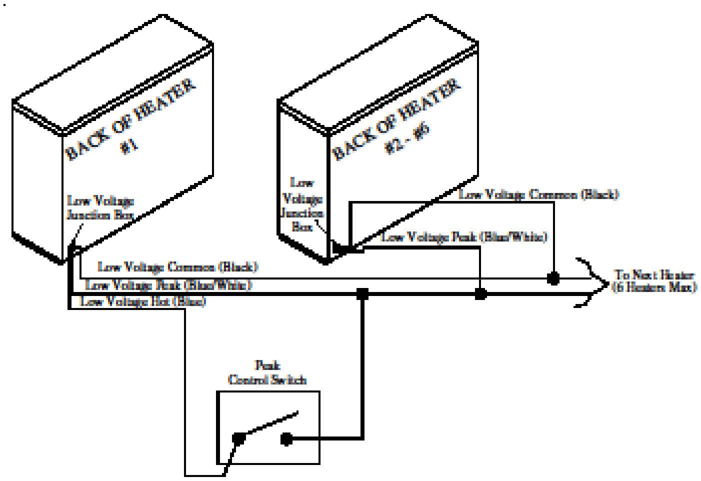
Multiple Feed Connection



NOTE: Connections shown are for systems with a 240V/208V blower/controls circuit.

Peak Control Options

- Low Voltage Control (See Diagram)
- Power Line Carrier (PLC) Control
  - Recommended for multiple heater installations
  - Requires the Steffes PLC transmitting device to be installed in the application to interface with each heaters built-in receiving system.
  - Refer to the Transmitter's Owner's and Installer's manual for more information on the operation and installation of the PLC control system.
- Time Clock Control
  - Requires the Steffes time clock module be installed in each heater to enable the heater's built-in time clock feature.
  - Refer to the time clock module's instruction sheet for information on the operation and installation of this device.
- Line Voltage Control
  - Requires an external switching device such as a relay panel to directly control the element circuits.
  - Blower/controls circuit must be powered with an uninterrupted circuit.



Specifications (For Standard 240VAC Systems)

Model	2102 (Plug-in)	2102	2103	2104	2105	2106
Charging Inputs (kW) -See Note 1	1.32	2.4 3.0 3.6	3.6 4.5 5.4	4.8 6.0 7.2	6.0 7.5 9.0	7.2 9.0 10.8
Approximate Installed Weight (lbs)	281	267	376	478	585	692
Storage Capacity -See Note 1 kWh BTU	13.5 46,062		20.25 69,093	27 92,124	33.75 115,155	40 136,480
Element Voltage - See Note 2	120	240 (Standard)				
Blower/Controls Voltage -See Note 3	120	240 (Standard)				
Blower Wattage -See Note 4 Minimum Maximum	30 120					

Note 1: The heating ability of each system is dependent upon the power company's available off-peak hours. Please contact Steffes Corporation for assistance in selecting the appropriate size and kW input of system required to satisfy a specific heat loss.

Note 2: 208 and 277 charging input voltage are also available as a special factory order. Standard 240V units can be connected to 208V; however, the heater will operate at 75% of its 240V rated input wattage.

Note 3: 240V is standard blower/controls voltage. 120 and 208 blower/controls voltage are also available as a special factory order.

Note 4: The blowers are variable speed.